WMB-2

Calibrated Multiport Large-Signal Measurement Setups for Outphasing, Doherty and Load Modulated Balanced Power Amplifiers

[1] Tibault Reveyrand,

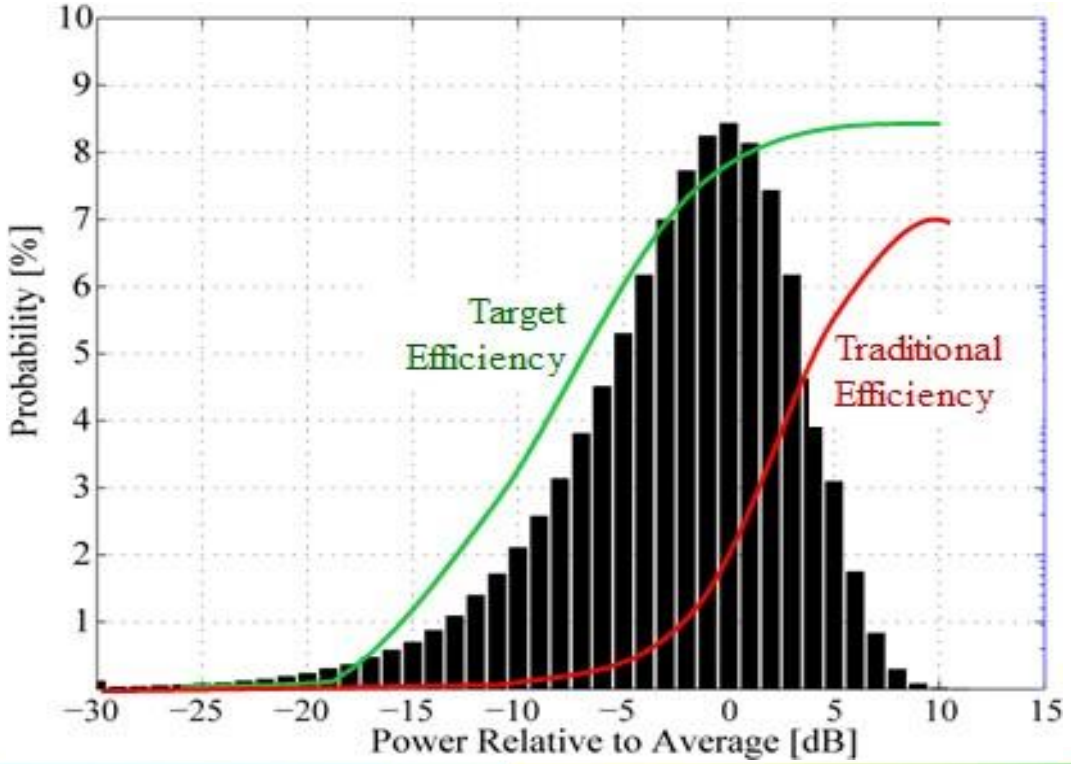
[1] Pierre Medrel, [1] Jean-Michel Nébus, and [2] Zoya Popović

[1] XLIM-CNRS, [2] CU-Boulder

Main challenges in PA design

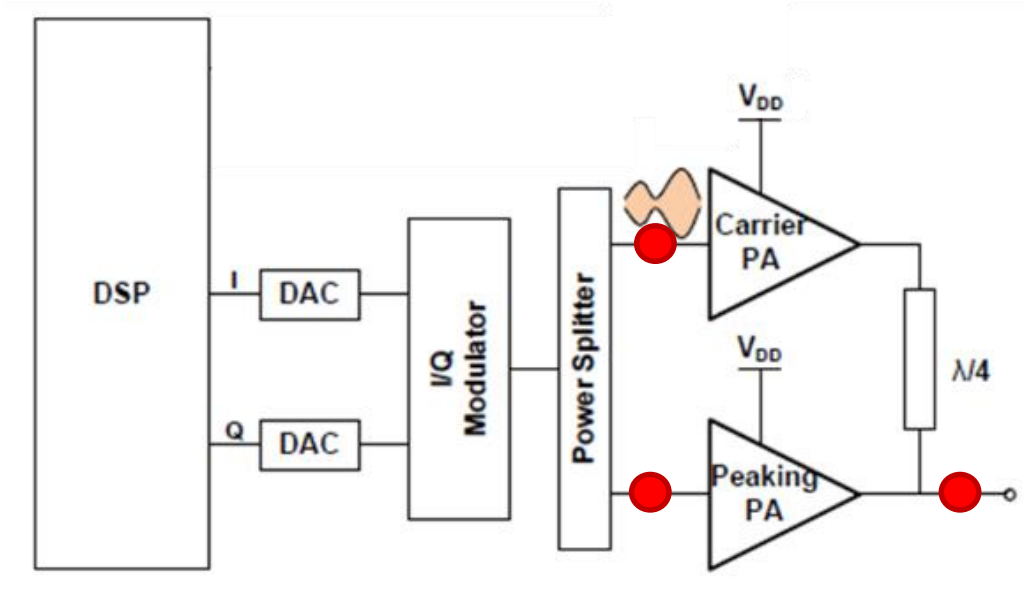
- Communications signals increasingly complex and broadband
- Signals vary in both amplitude and phase – PAPR, PDF and CCDF criteria
- It is difficult to transmit such signal with high efficiency transmitters

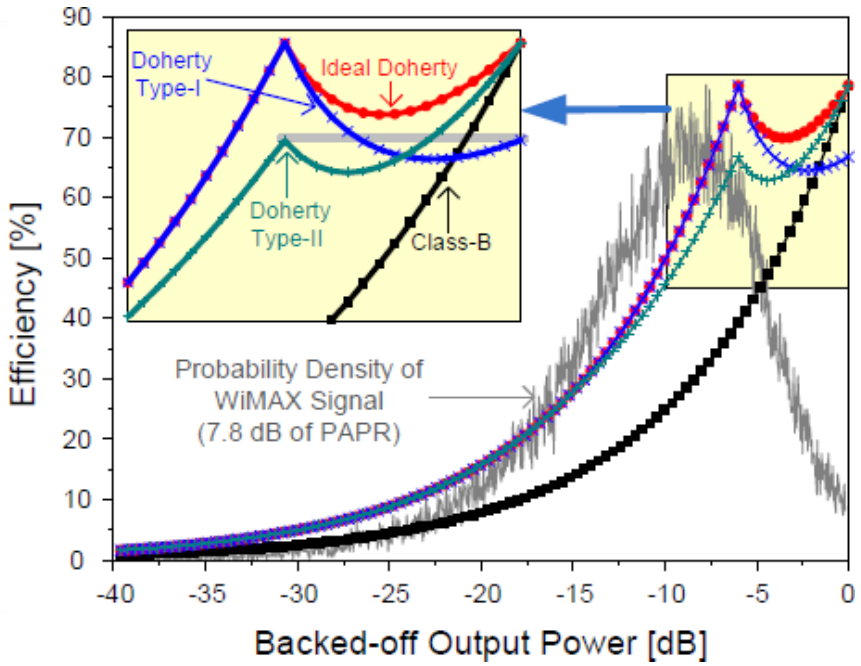
- Efficiency drops as output power drops
- Efficient PAs are nonlinear
- Output Load can vary

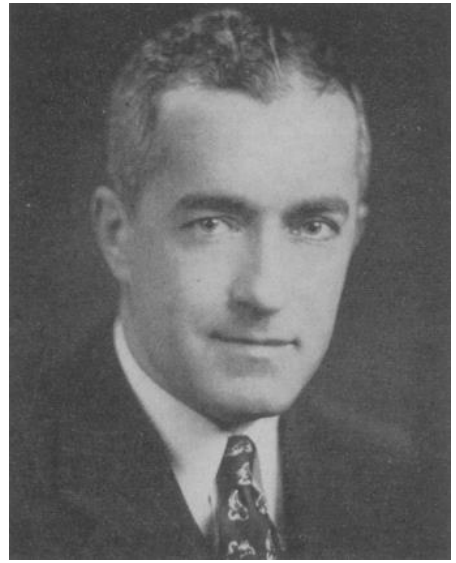


Doherty Amplifier

W. Doherty, "A new high efficiency power amplifier for modulated waves," *Proc. IRE*, vol. 24, no. 9, pp. 1163–1182, Sep. 1936.



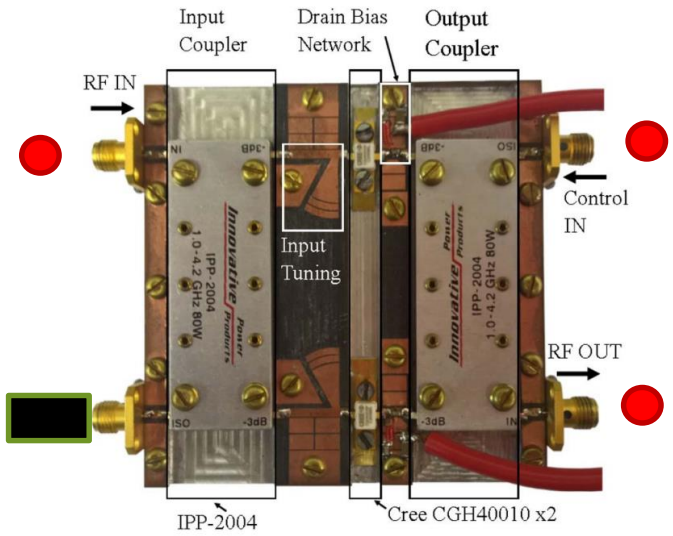


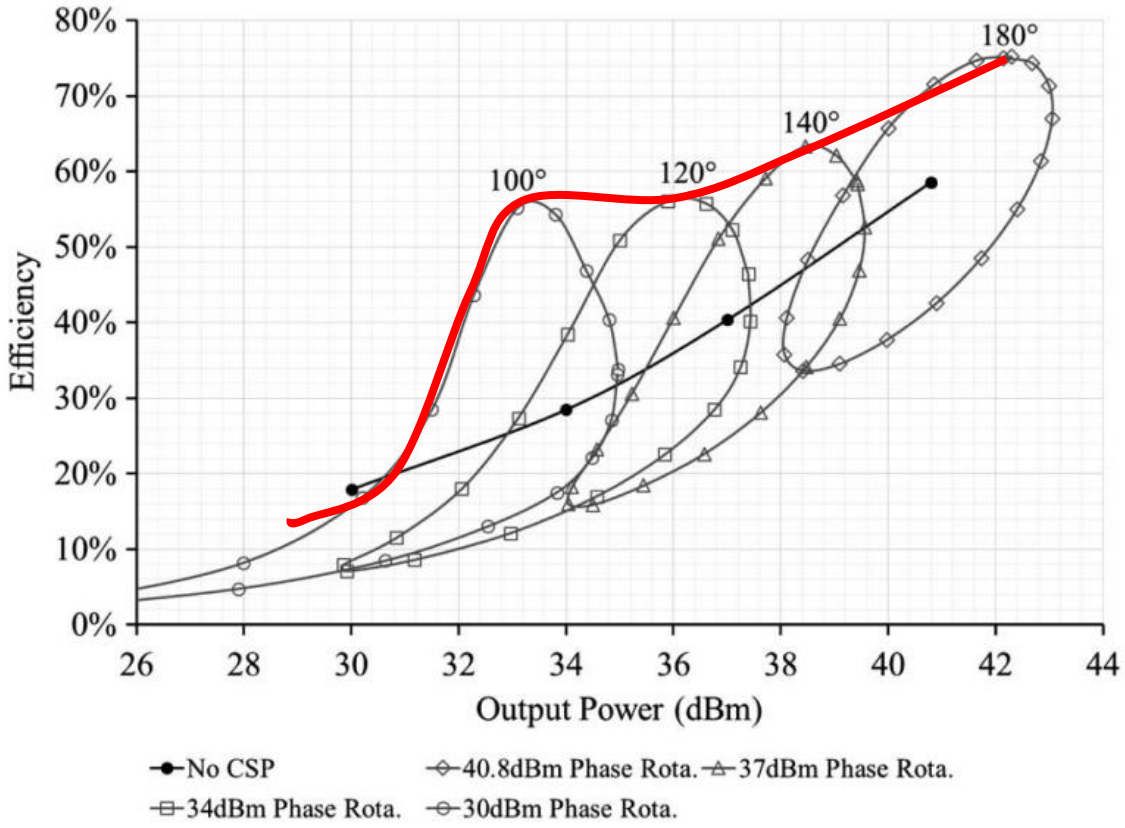


From B. Kim et al, 2010

Load Modulated Balanced Amplifier

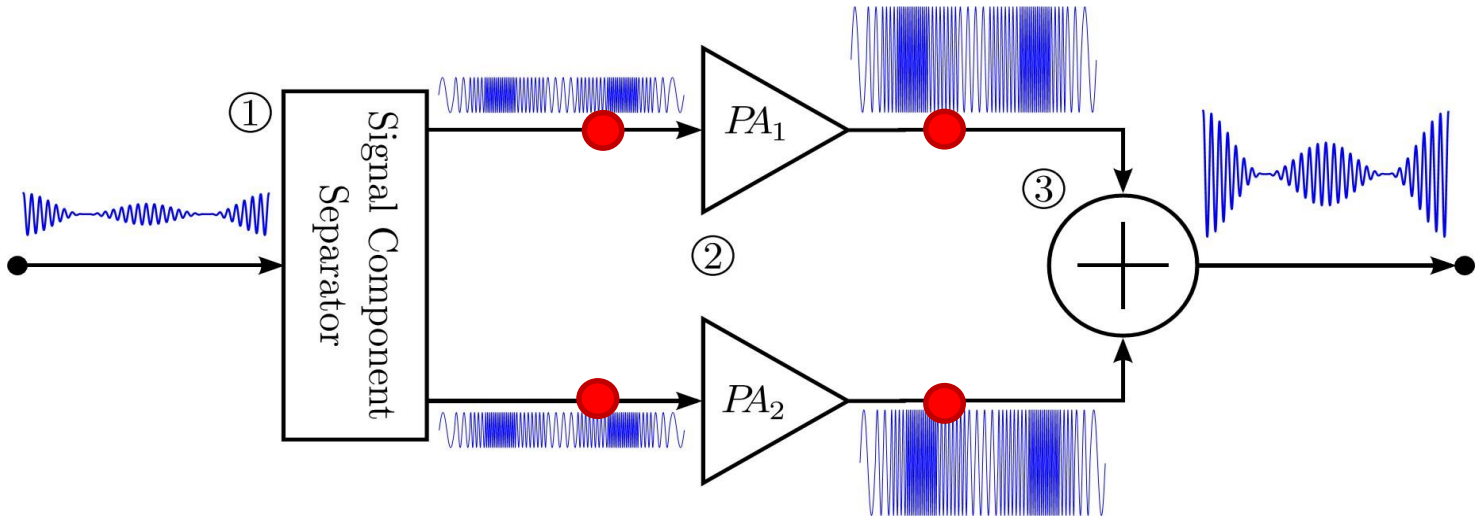
Daniel J. Shepphard, Jeffrey Powell, and Steve C. Cripps, "An Efficient Broadband Reconfigurable Power Amplifier Using Active Load Modulation," *IEEE Microwave and Wireless Components Letters* , vol. 26, no. 6, pp. 443–445, May 2016.





Outphasing Amplifier

H. Chireix, "High power outphasing modulation,", *Proc. IRE*, vol. 23, no. 11, pp. 1370–1392, Nov. 1935



- Amplitude modulation converted to additional phase modulation
- High-efficiency PAs driven with constant envelope
- Combiner reconstructs envelope through vector addition
- Combiner can be isolated or non-isolated

Main challenges in PA design

Digital dual input PAs add another degree of freedom to the sub-system to optimize :

- the Linearity / Efficiency trade-off ;
- the design of the input combiner or driver for a RF power amplifier ;
- the Digital Pre Distortion (DPD).

NEED FOR
MULTIPORT CALIBRATED NONLINEAR MEASUREMENTS

Outline of the presentation

- Power-meter based measurements
  - Setup and calibration of the RF source
  - Example on a Digital Doherty RF PA
  - Example on a Digital RF LMBA

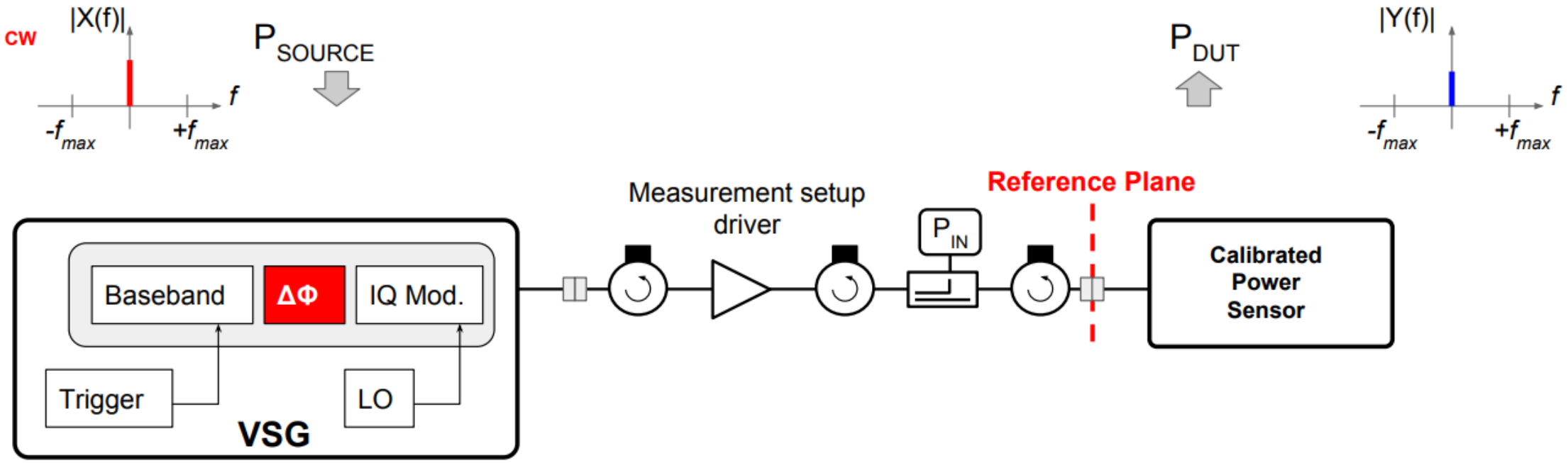
- NVNA based measurements
  - Example on a Digital Outphasing RF PA
  - Generalized NVNA Calibration

Outline of the presentation

- **Power-meter based measurements**
  - Setup and calibration
  - Example on a Digital Doherty RF PA
  - Example on a Digital RF LMBA

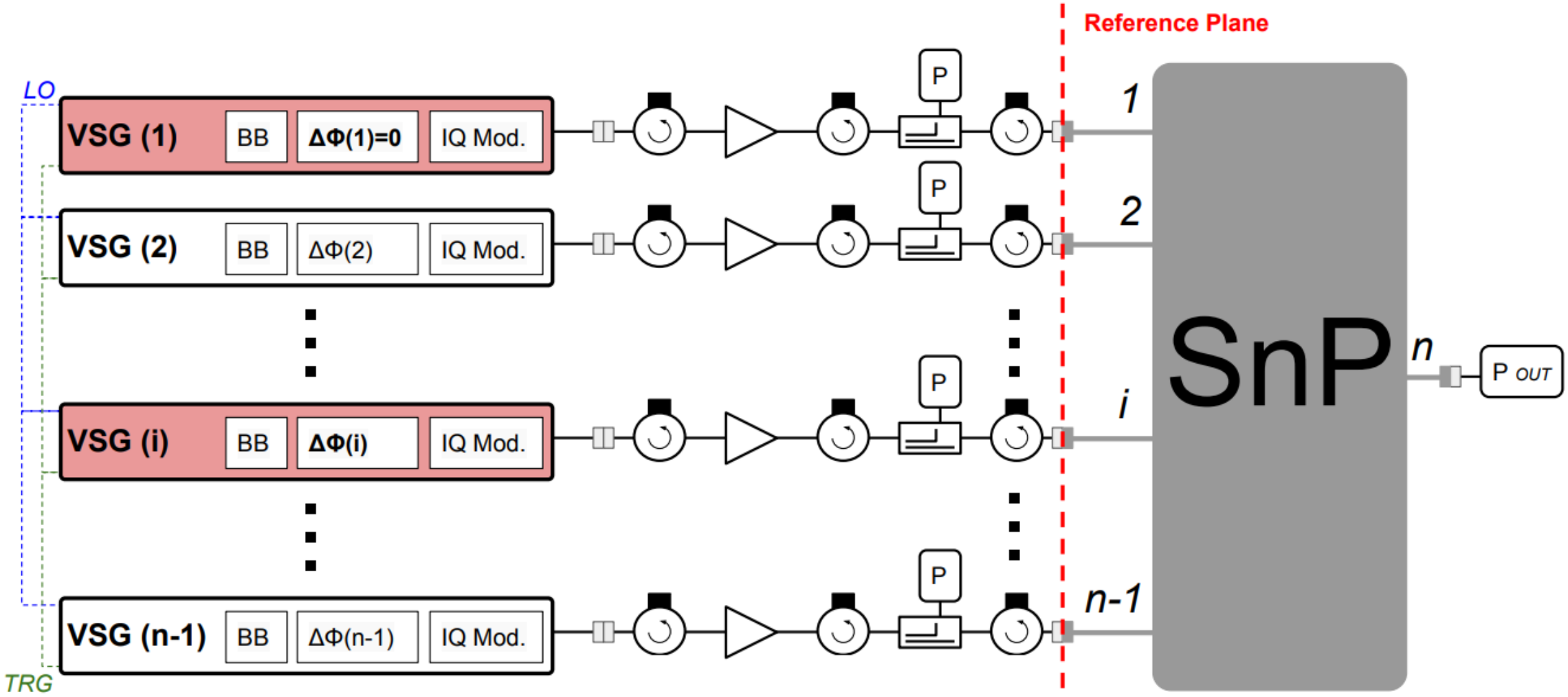
- NVNA based measurements
  - Example on a Digital Outphasing RF PA
  - Generalized NVNA Calibration

1-Port CW Power Calibration

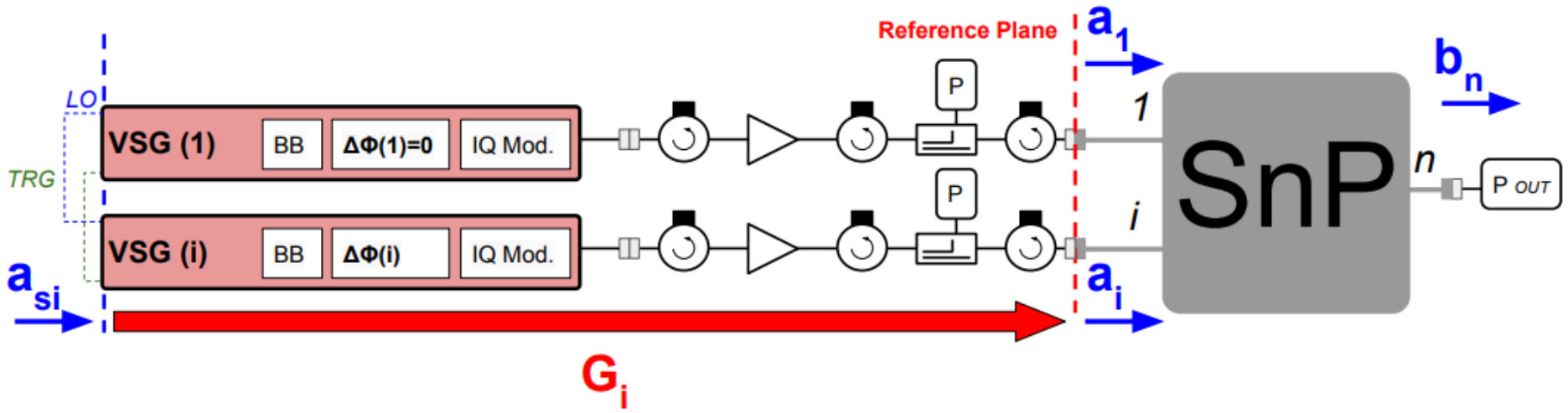


- CW signal can be obtained from a time constant complex envelope. Control of the phase of the carrier (LO) is performed by applying a phase offset on the frequency domain IQ modulation. This phase control is essential for the "Multiport Source".
- Magnitude calibration procedure consists in identifying $|G_1|^2 = \Delta P = \frac{P_{DUT}}{P_{SOURCE}}$.

Principle of a Multi-source Calibration



Multi-source Calibration



$$b_n = S_{n1}.a_1 + S_{ni}.a_i$$

$$|b_n|^2 = |S_{n1}.a_1 + S_{ni}.G_i.a_{si}|^2$$

$$A.|G_i|^2 + B.\Re\{G_i\} + C.\Im\{G_i\} = D$$

with

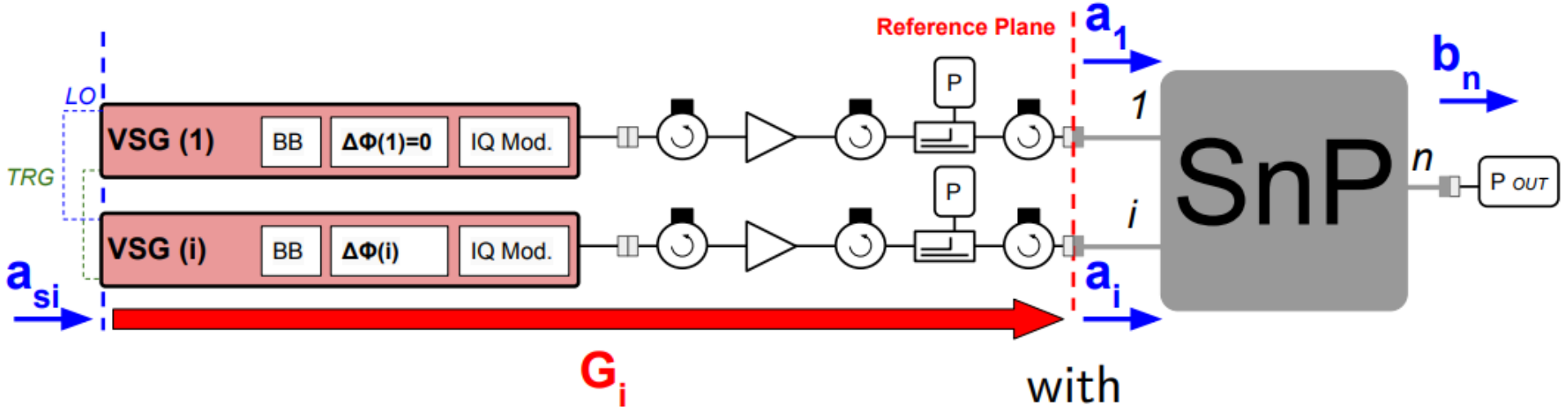
$$A = |S_{ni}.a_{si}|^2$$

$$B = 2.\Re\{S_{n1}^*.a_1^*.S_{ni}.a_{si}\}$$

$$C = -2.\Im\{S_{n1}^*.a_1^*.S_{ni}.a_{si}\}$$

$$D = |b_n|^2 - |S_{n1}.a_1|^2$$

Multi-source Calibration



$$\begin{pmatrix} |G_i|^2 \\ \Re\{G_i\} \\ \Im\{G_i\} \end{pmatrix} = \begin{bmatrix} A(\phi_A) & B(\phi_A) & C(\phi_A) \\ A(\phi_B) & B(\phi_B) & C(\phi_B) \\ A(\phi_C) & B(\phi_C) & C(\phi_C) \\ \vdots & \vdots & \vdots \end{bmatrix}^{\dagger} \cdot \begin{pmatrix} D(\phi_A) \\ D(\phi_B) \\ D(\phi_C) \\ \vdots \end{pmatrix}$$

where $\bullet^{\dagger}$ denotes the pseudo-inverse operator.

with

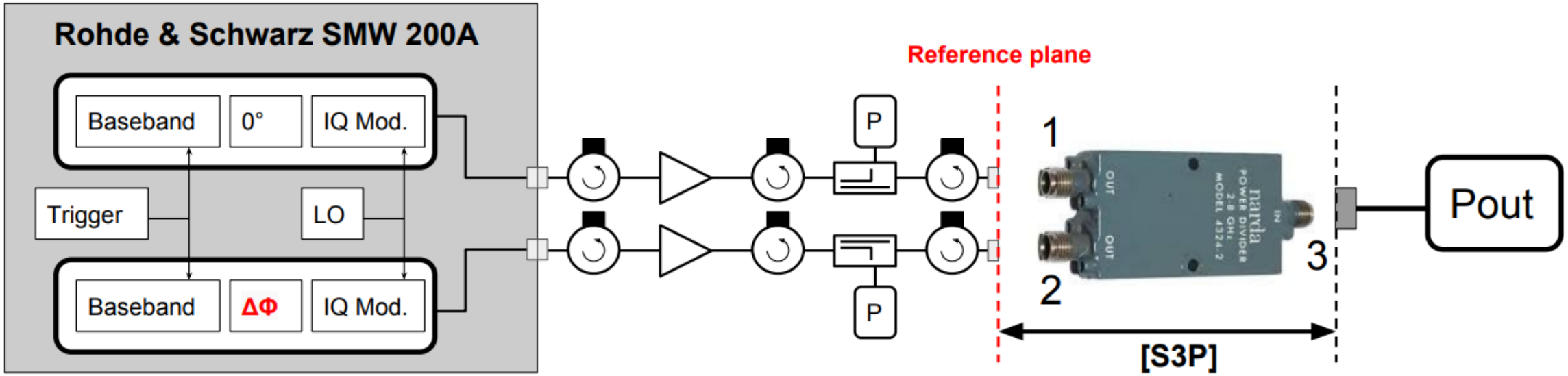
$$A = |S_{ni}.a_{si}|^2$$

$$B = 2.\Re\{S_{n1}^*.a_1^*.S_{ni}.a_{si}\}$$

$$C = -2.\Im\{S_{n1}^*.a_1^*.S_{ni}.a_{si}\}$$

$$D = |b_n|^2 - |S_{n1}.a_1|^2$$

Multi-source Calibration Validation



- **Uncalibrated phase:** $\mathrm{Arg}\{a_2\} = \Delta\Phi$ is entered in the instrument ;
- **Calibrated phase:** $\mathrm{Arg}\{a_2\} = \Delta\Phi$ is referenced at the DUT reference plane. The instrument value takes into account the phase shift between the digital command and the RF reference plane ;
- **Simulation:** $\mathrm{Arg}\{a_2\} = \Delta\Phi$ is calculated from the measured powers and the S3P file assuming $\mathrm{Arg}\{a_1\} = 0$.

Multi-source Calibration Validation

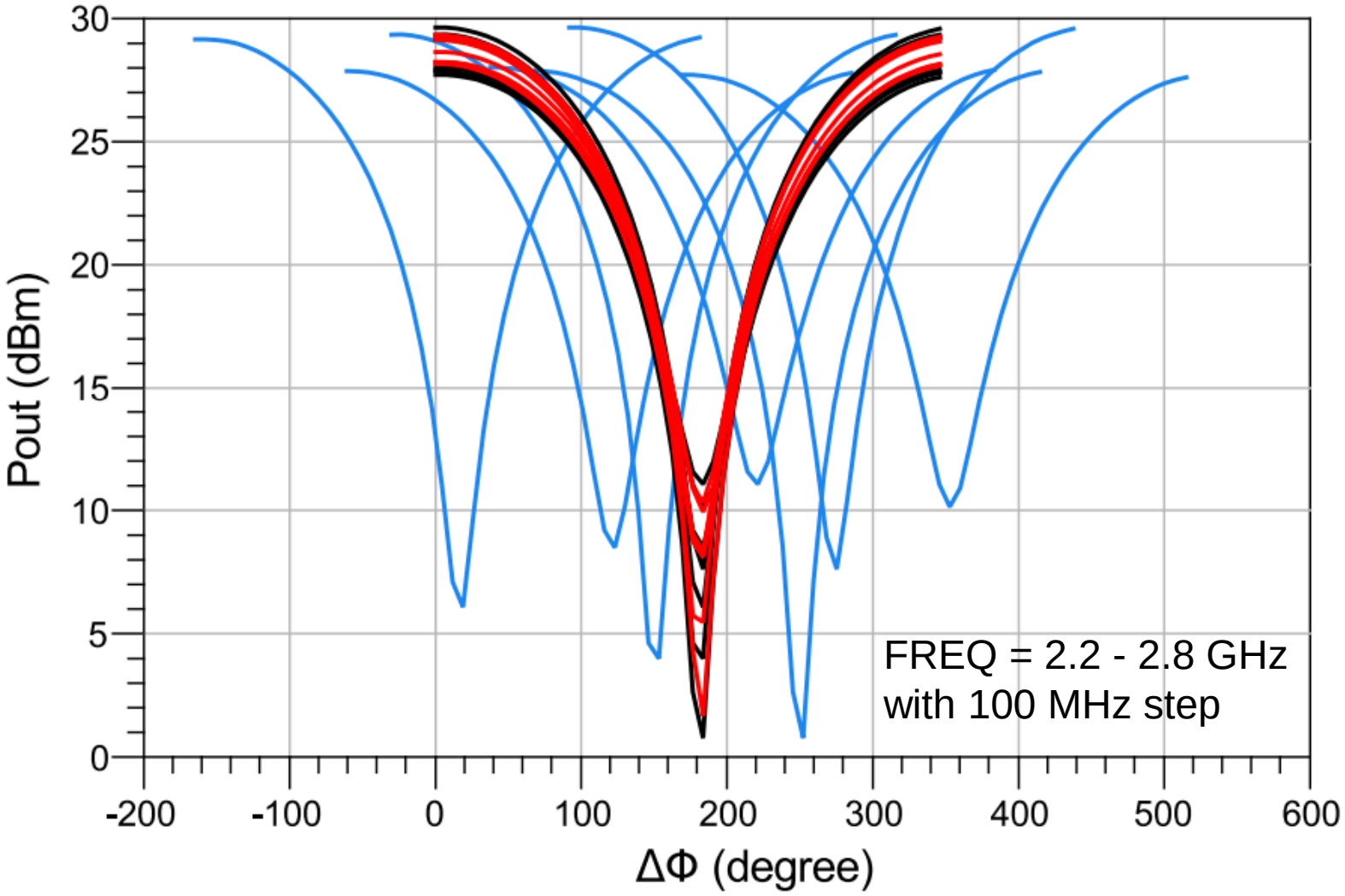
Measurements:

Uncalibrated phase

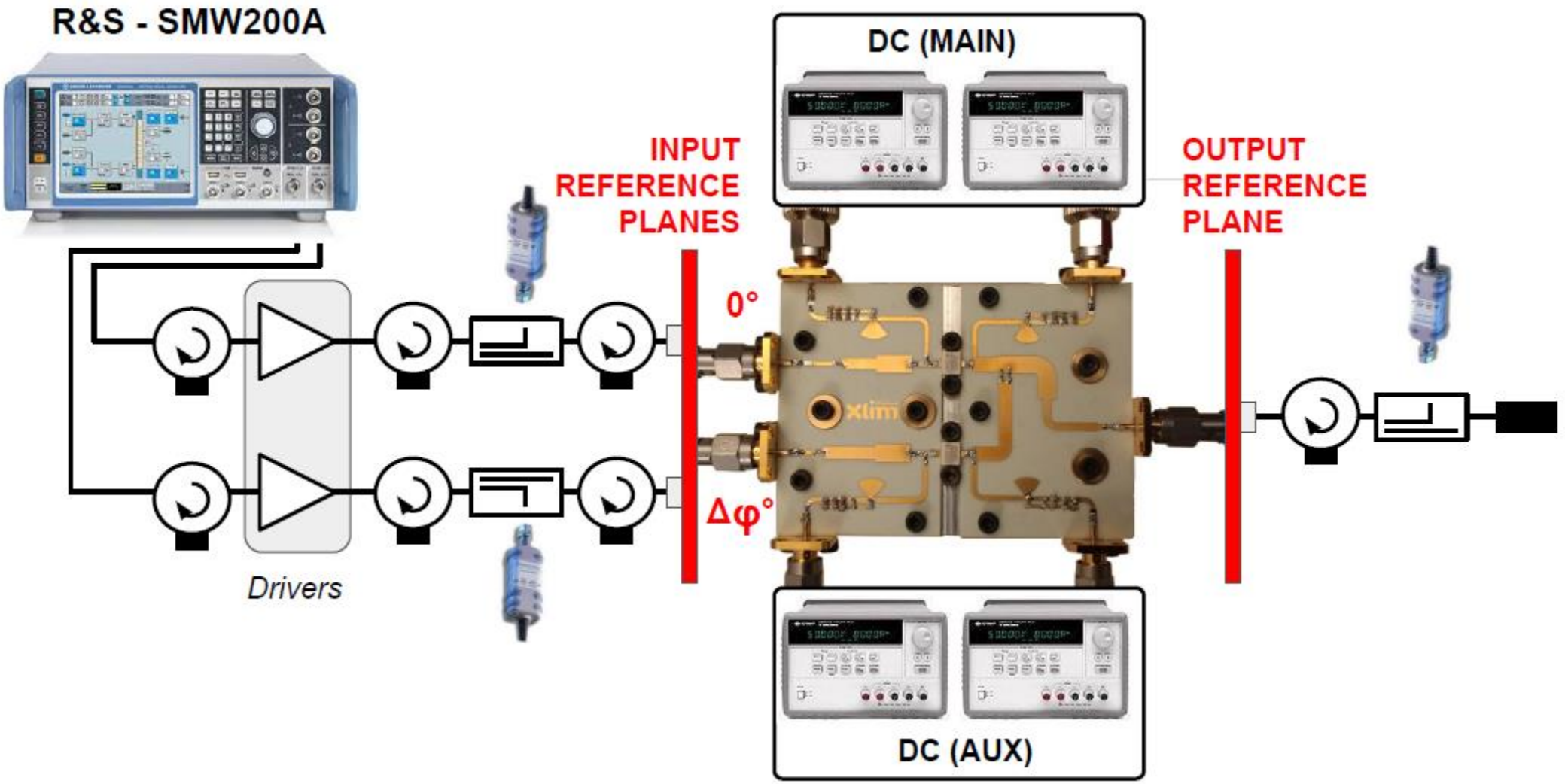
Calibrated phase

Simulation:

ΔΦ calculated from Pin1, Pin2, Pout and S3P file

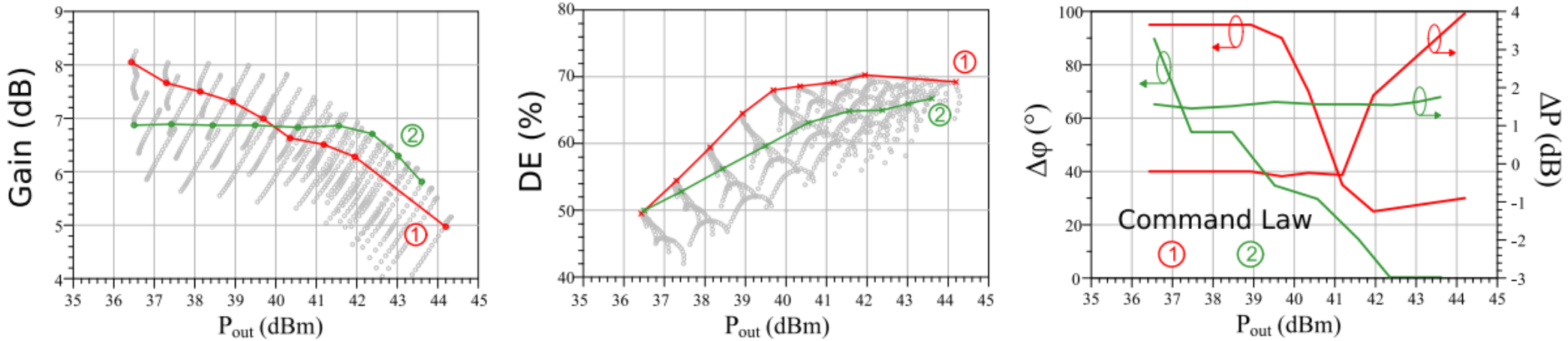


Digital Doherty CW Measurements



Digital Doherty Mesurements

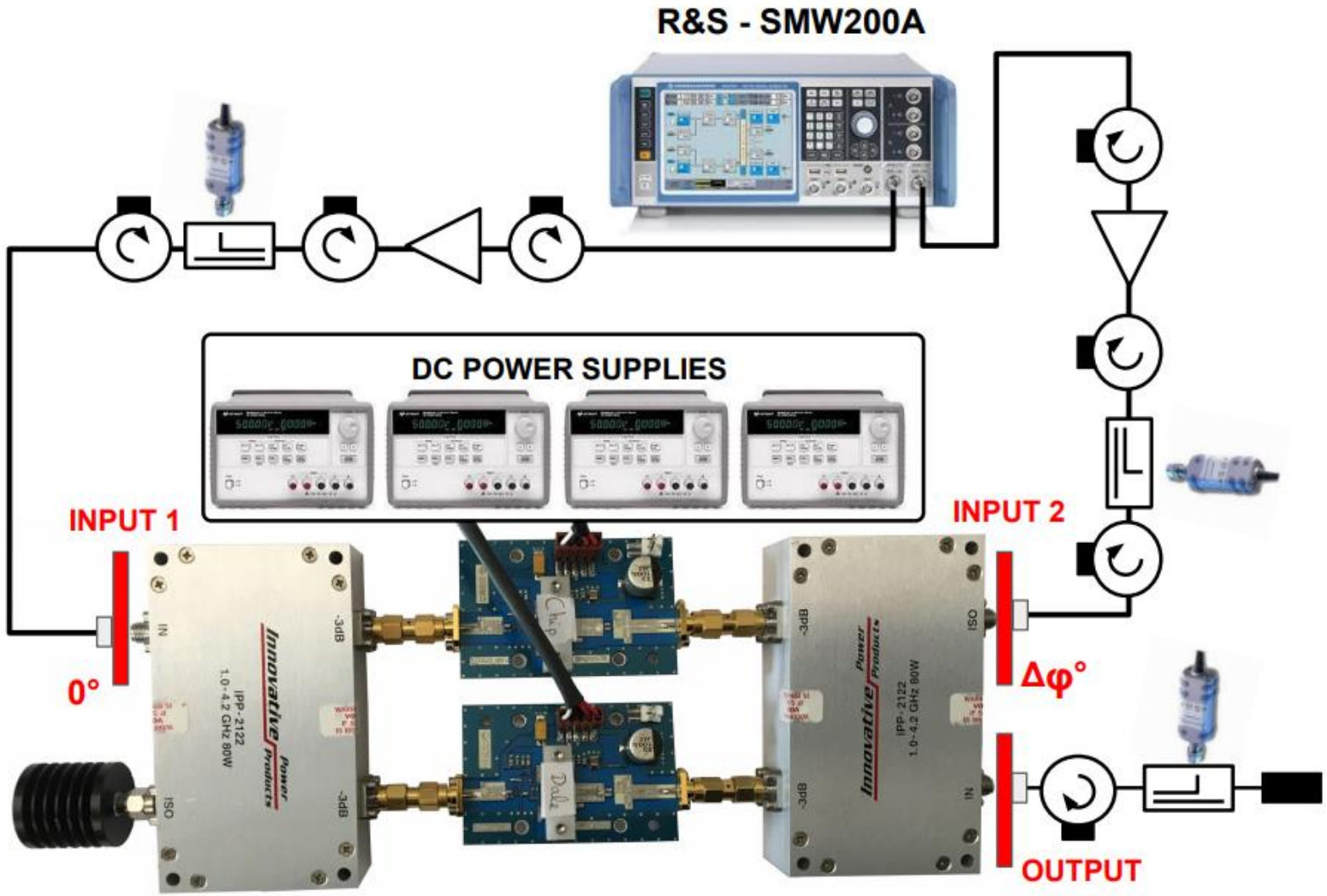
P_{in} is the available power at the input of the **Main** amplifier.
We focus on the magnitude and phase imbalance between the two inputs.
ΔP and $\Delta\varphi$ are swept for each value of P_{in}



Then, we can sort out the best digital control of the Doherty in term of:

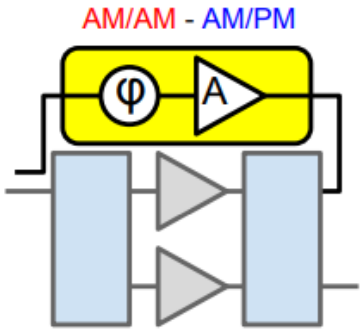
- **efficiency** ;
- **linearity**.

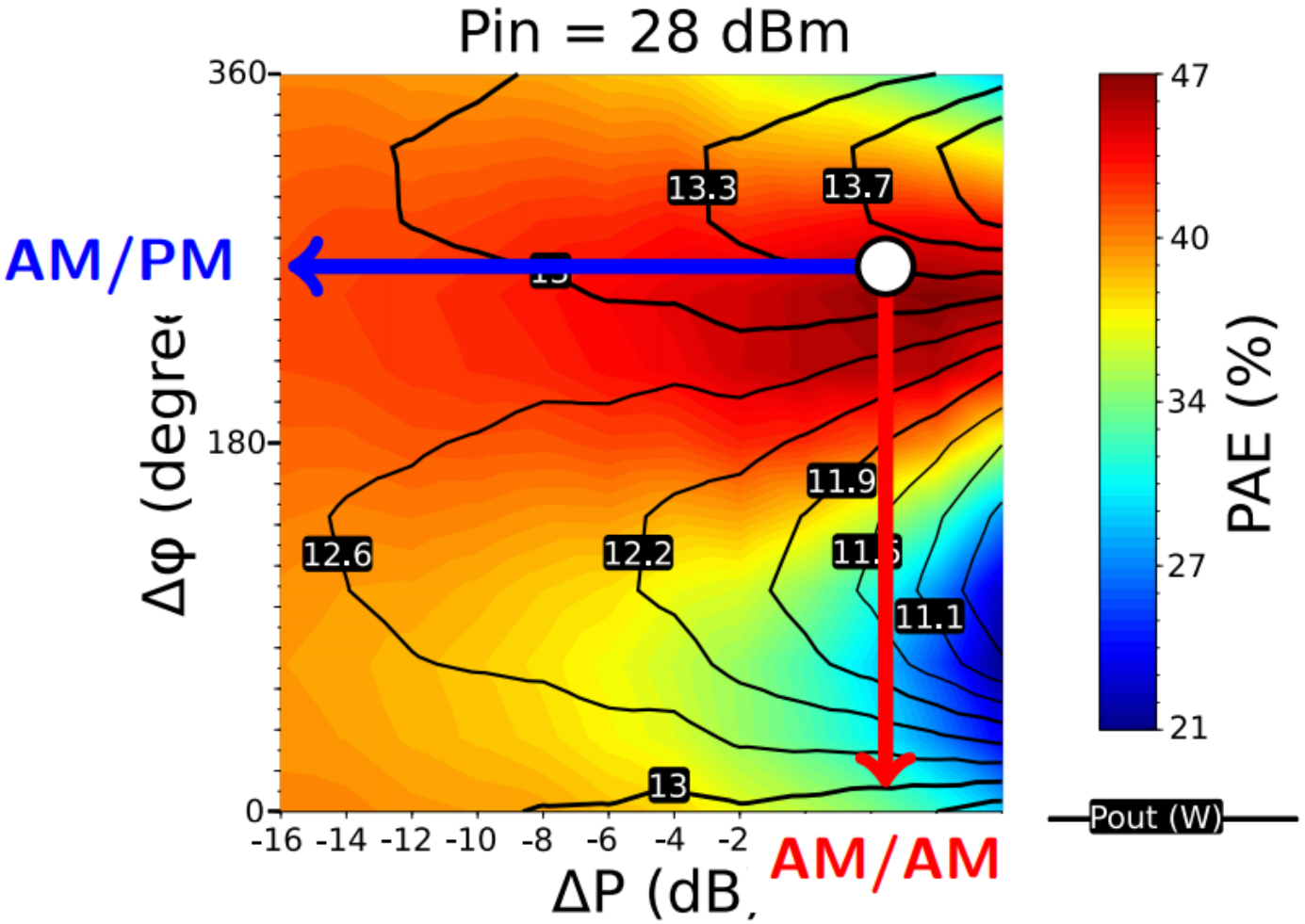
LMBA Measurements



Digital LMBA CW Measurements

- Direct performance plot at each CW input power ;
- Investigate internal Load-Pull effect ;
- Visual extraction of **AM/AM** and **AM/PM** of the RF auxiliary path according to the selected trade-off.



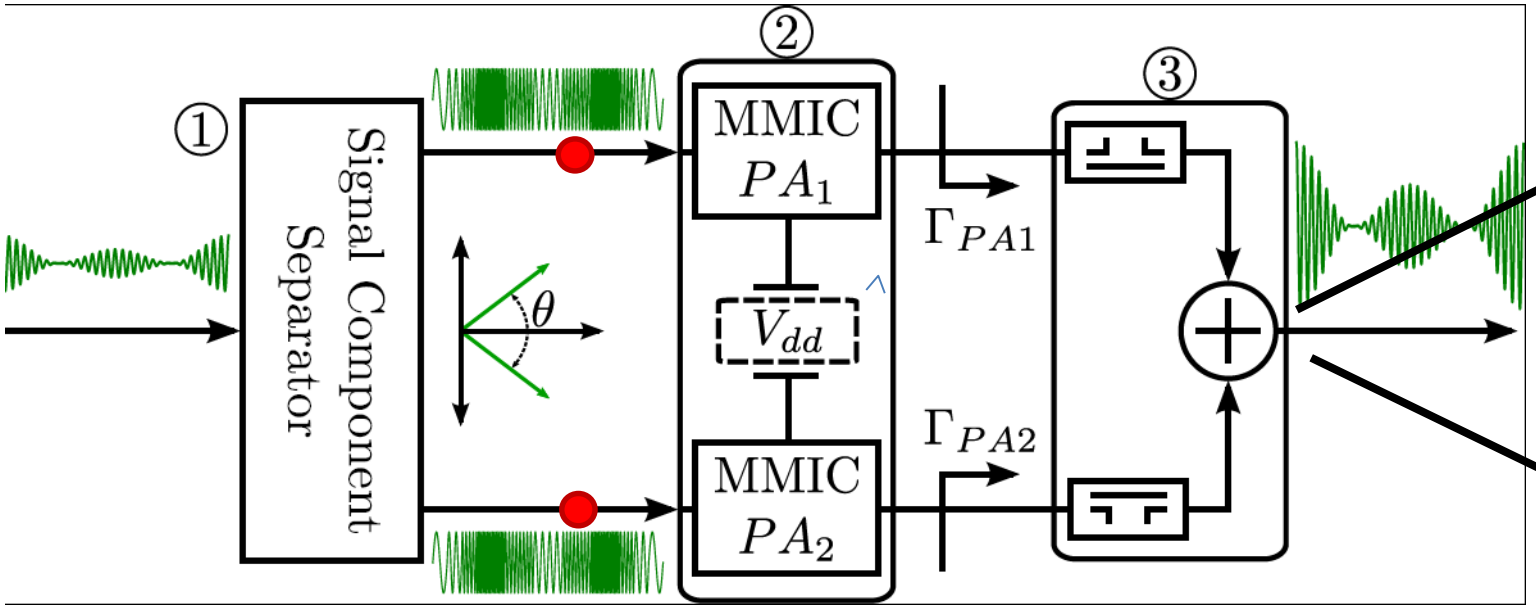


Outline of the presentation

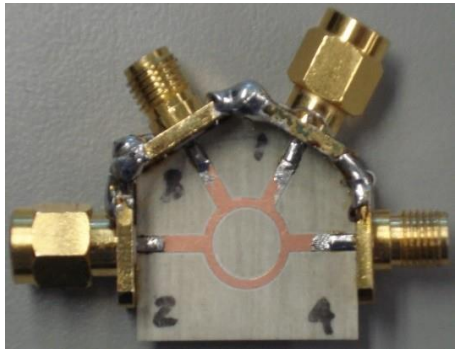
- Power-meter based measurements
  - Setup and calibration
  - Example on a Digital Doherty RF PA
  - Example on a Digital RF LMBA

- **NVNA based measurements**
  - Example on a Digital Outphasing RF PA
  - Generalized NVNA Calibration

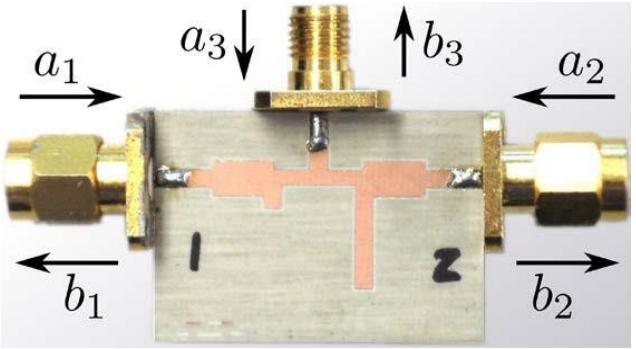
Outphasing characterization



ISOLATED COMBINER

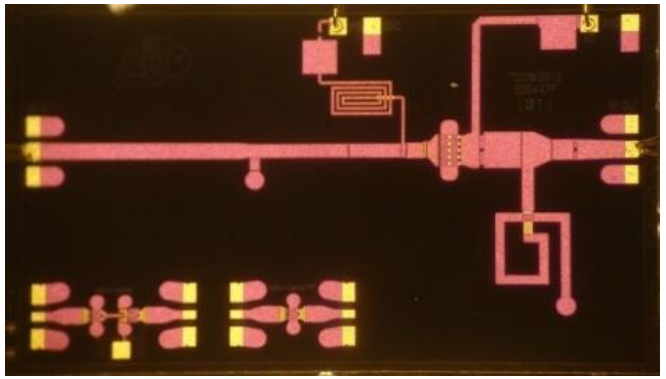


NON-ISOLATED COMBINER



● Digital Inputs

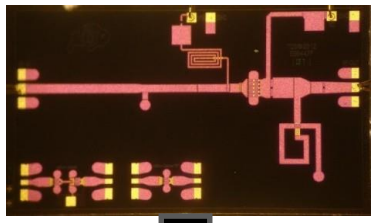
M. Litchfield et al. (2015)

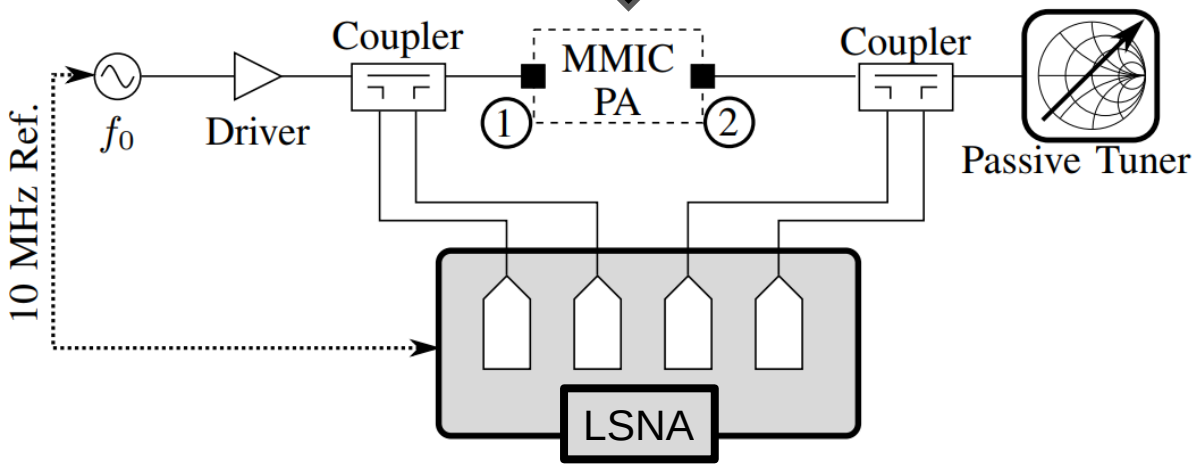


- MMIC 3 Watts 10 GHz PA (TriQuint 0.15 µm)
- Load pull of a single PA done with LSNA

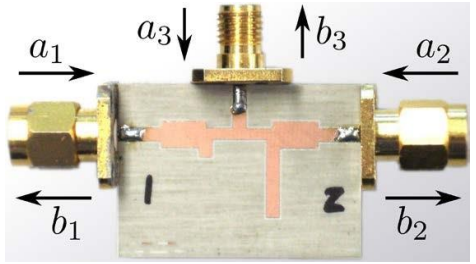
Non-isolated Combiner based on Load-Pull

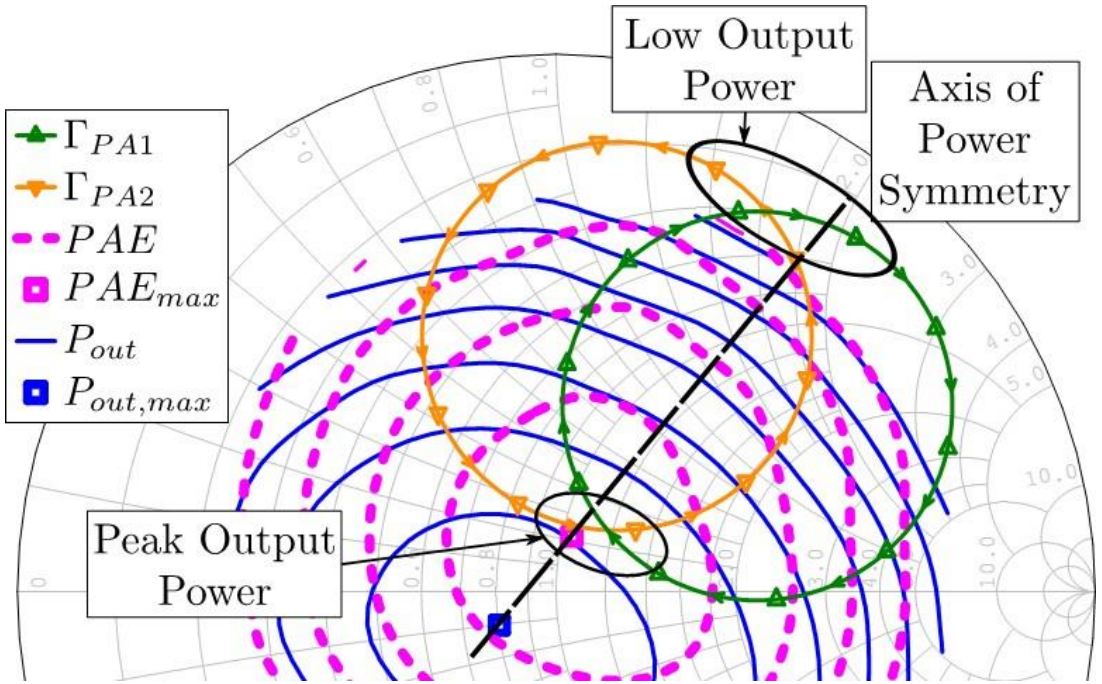
Load-Pull
on a single PA



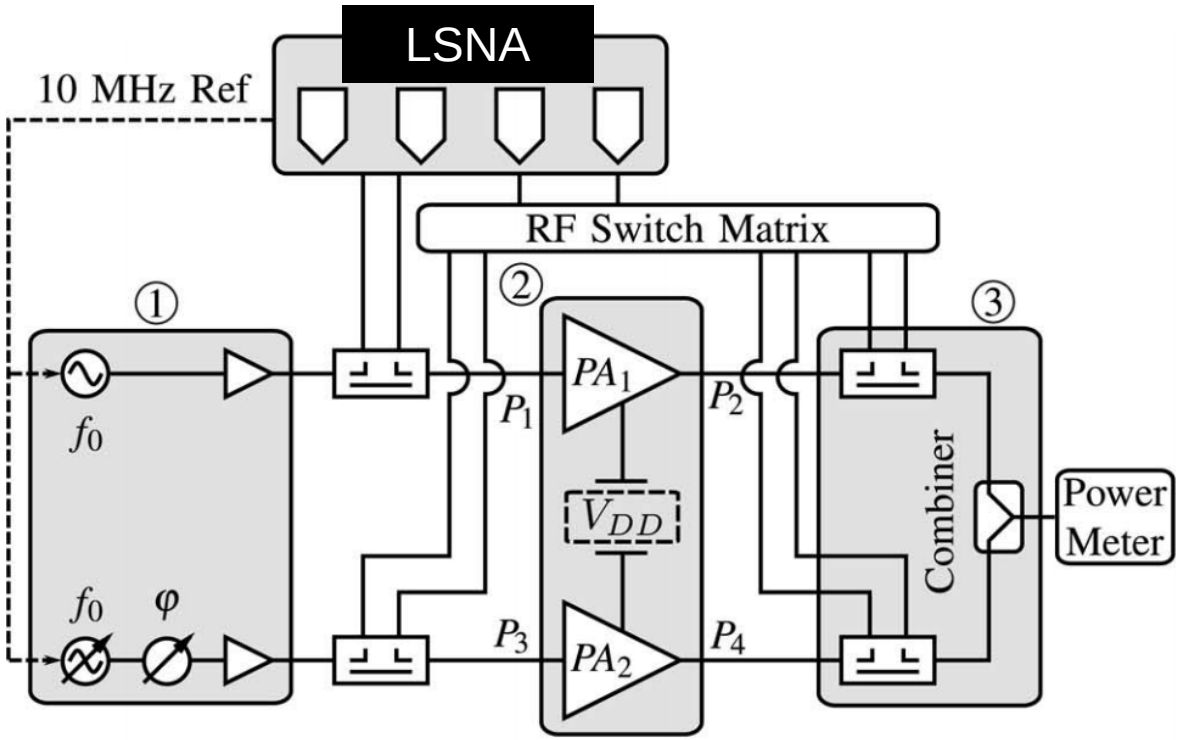


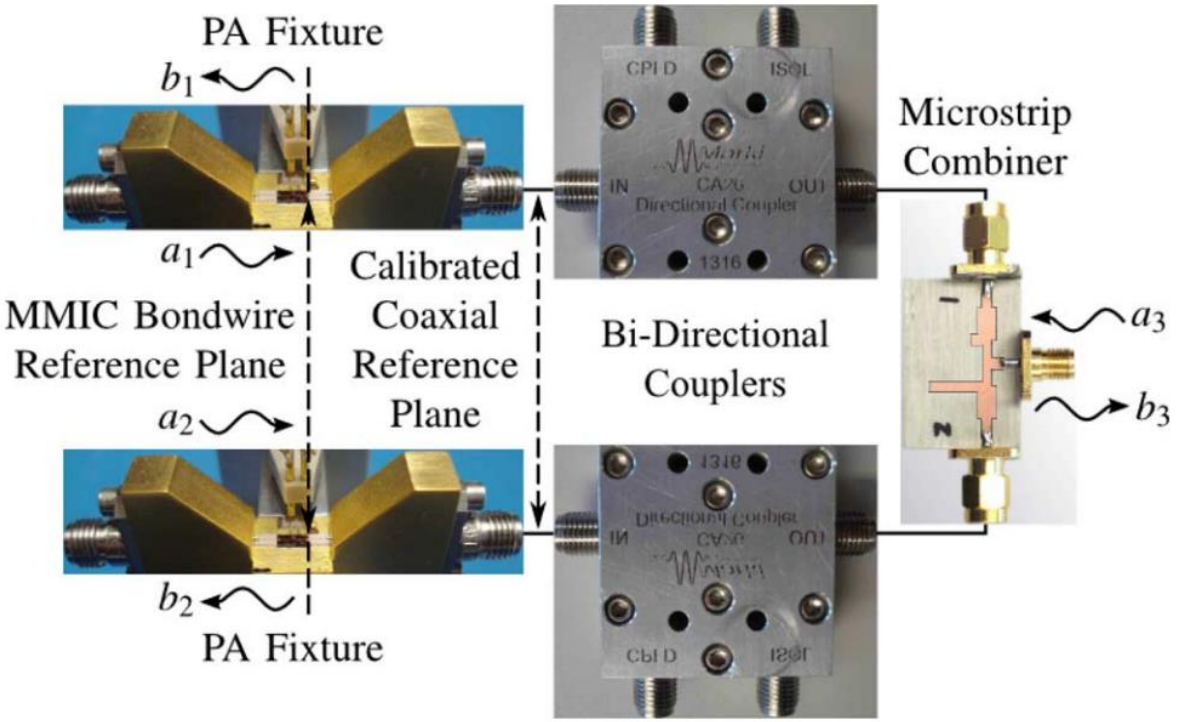
Design of the
non-isolated
combiner



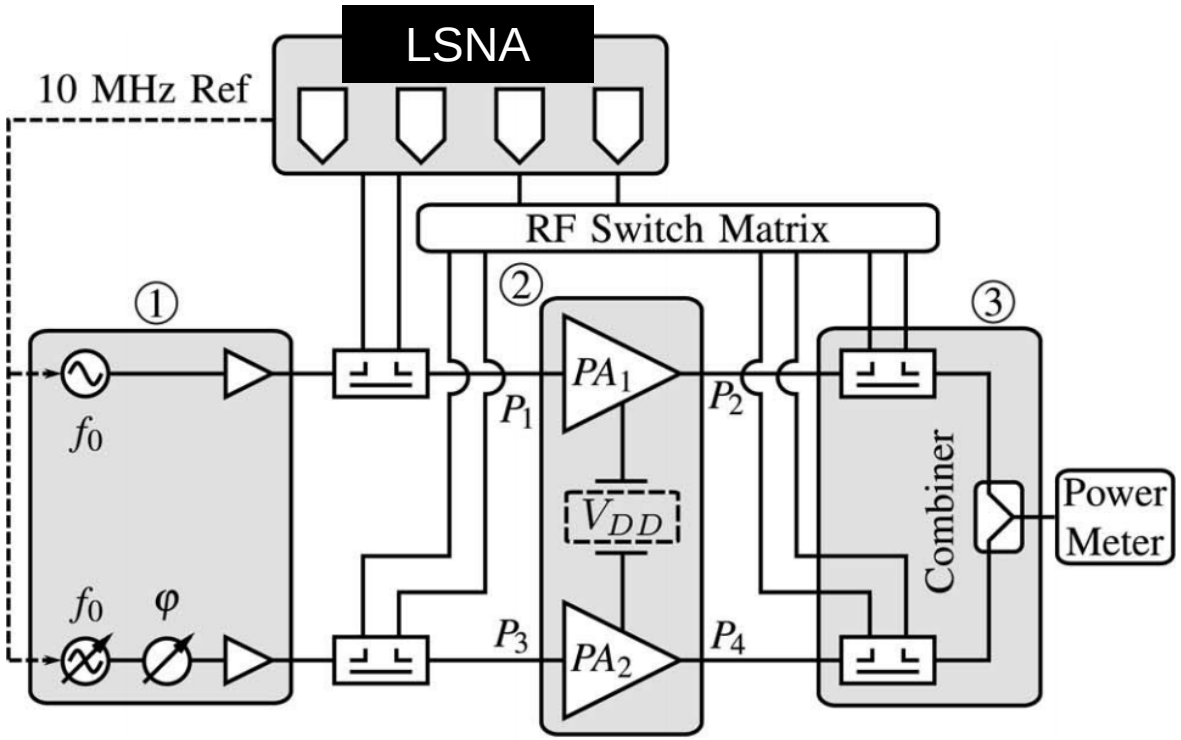


Outphasing PA : Internal characterization





Outphasing PA : Internal characterization

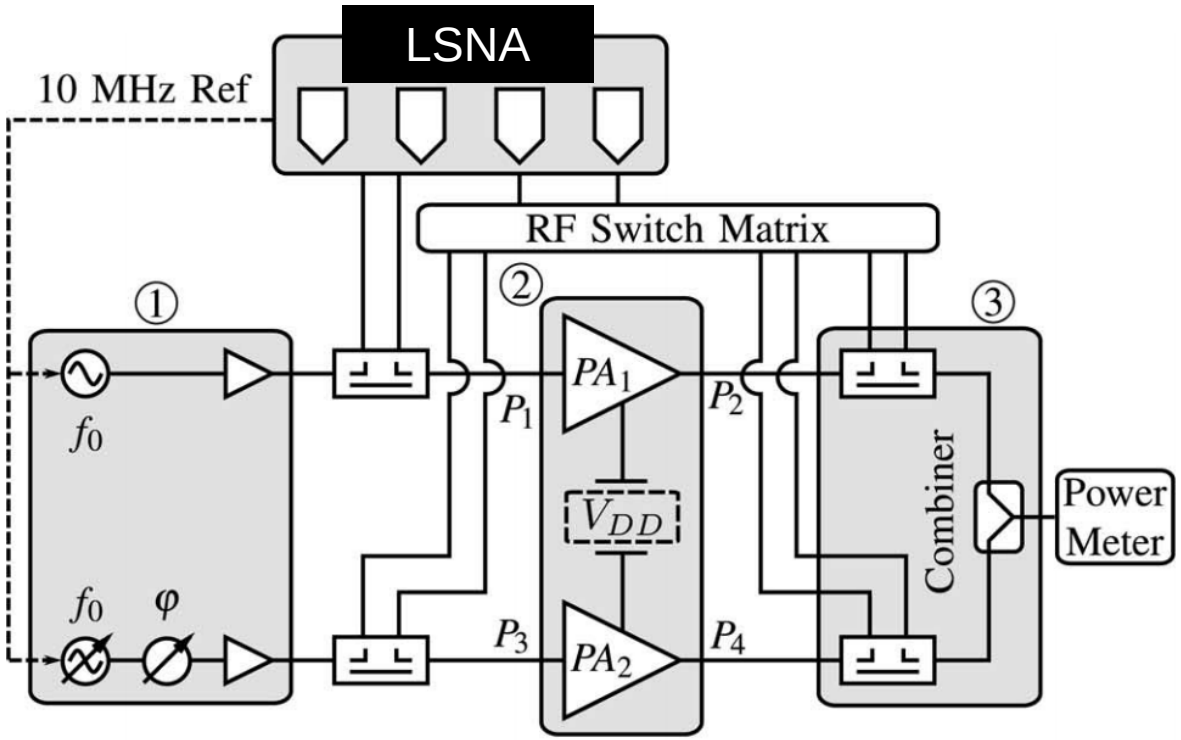


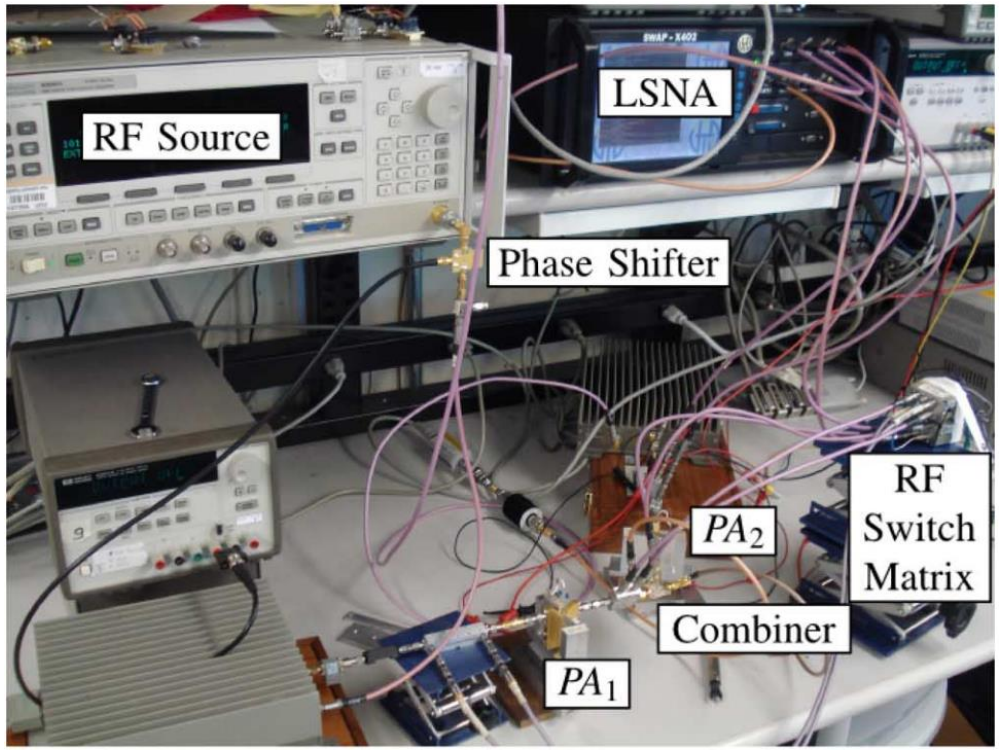
SOLT Calibration on a 2-port LSNA

3 configurations are considered

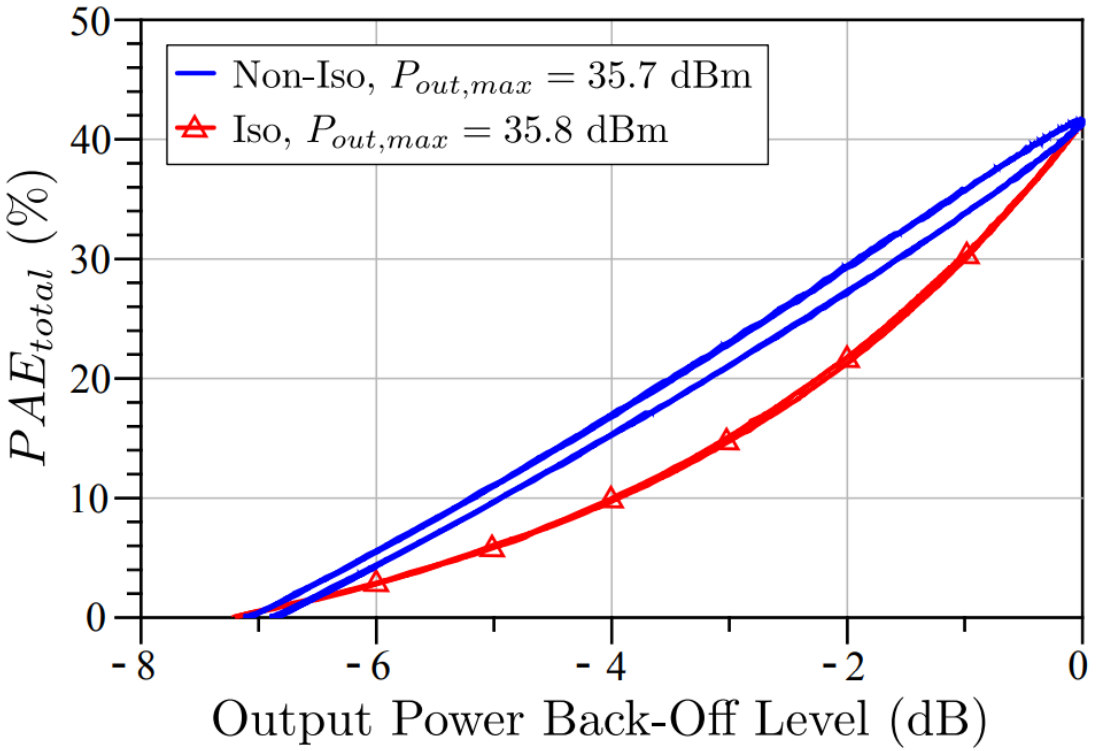
Switch 1 : LSNA Port 1 - Port 2
Switch 2 : LSNA Port 1 - Port 4
Switch 3 : LSNA Port 2 - Port 4

Outphasing PA : Internal characterization

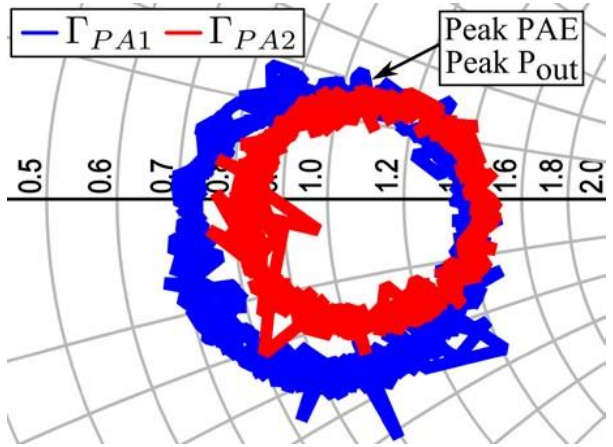




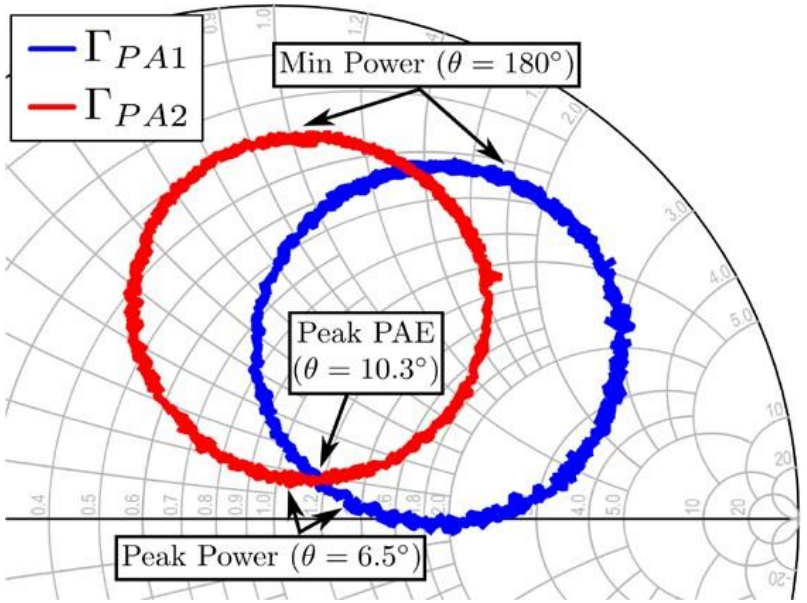
Outphasing PA : Comparison



Isolated

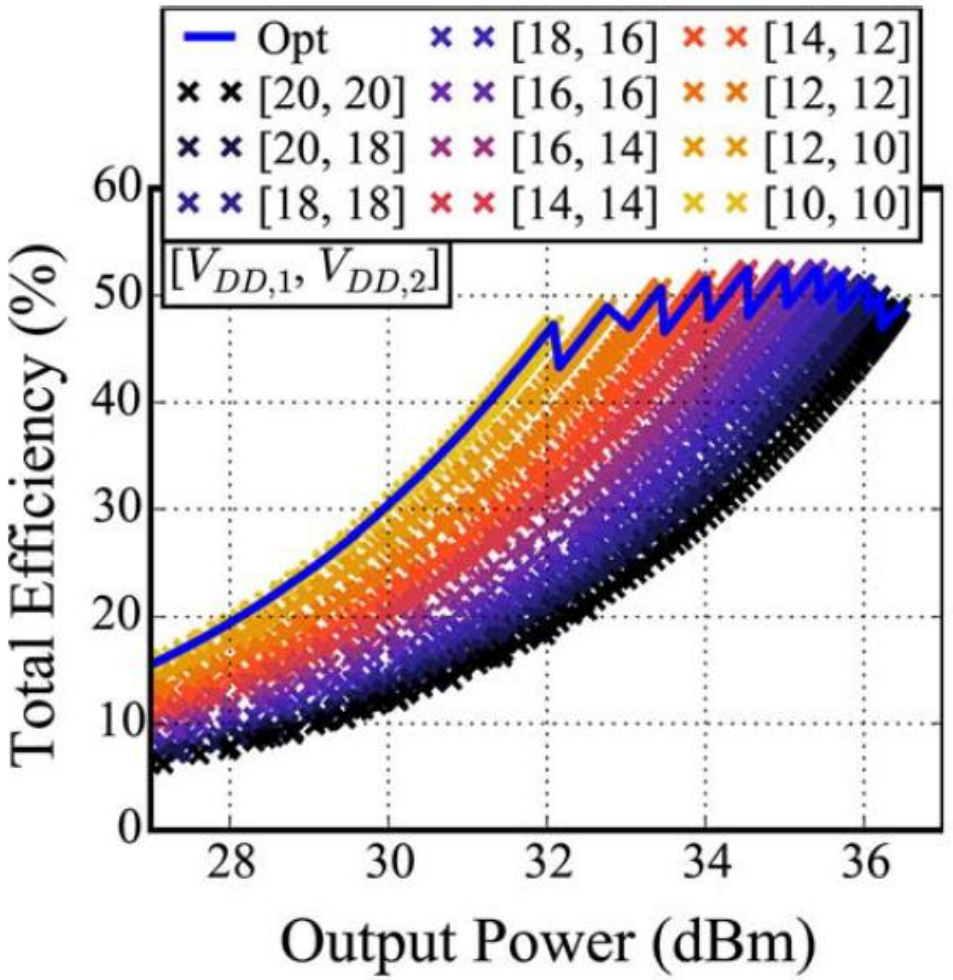


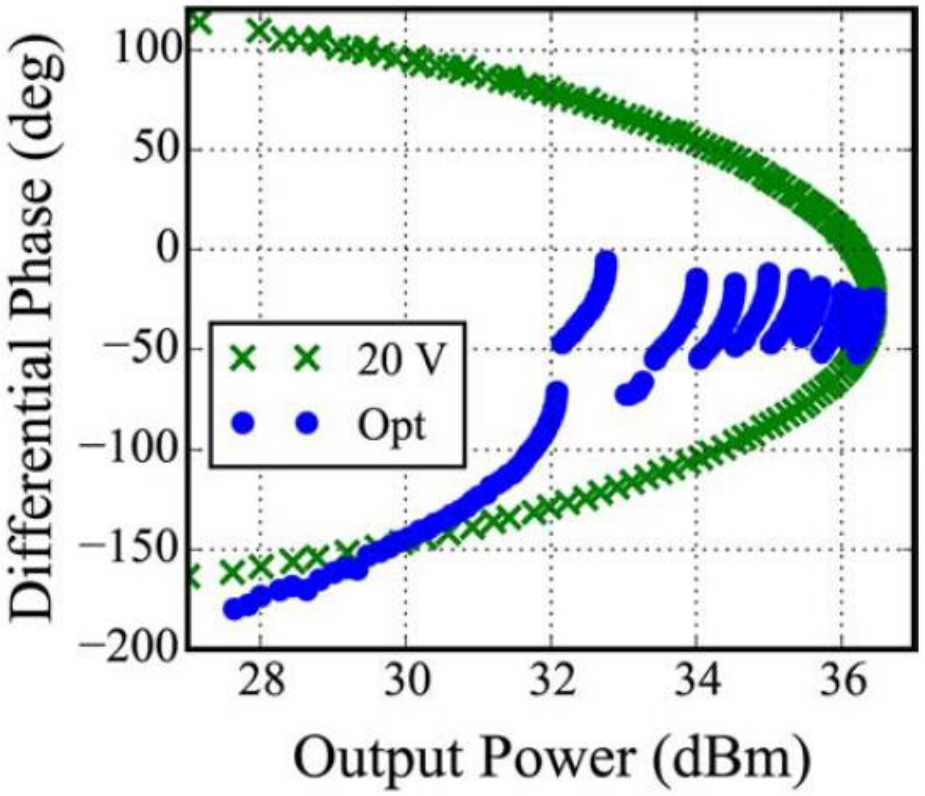
Non-isolated



AMO PA Measurements

AMO: Asymmetric Multi-Level Outphasing



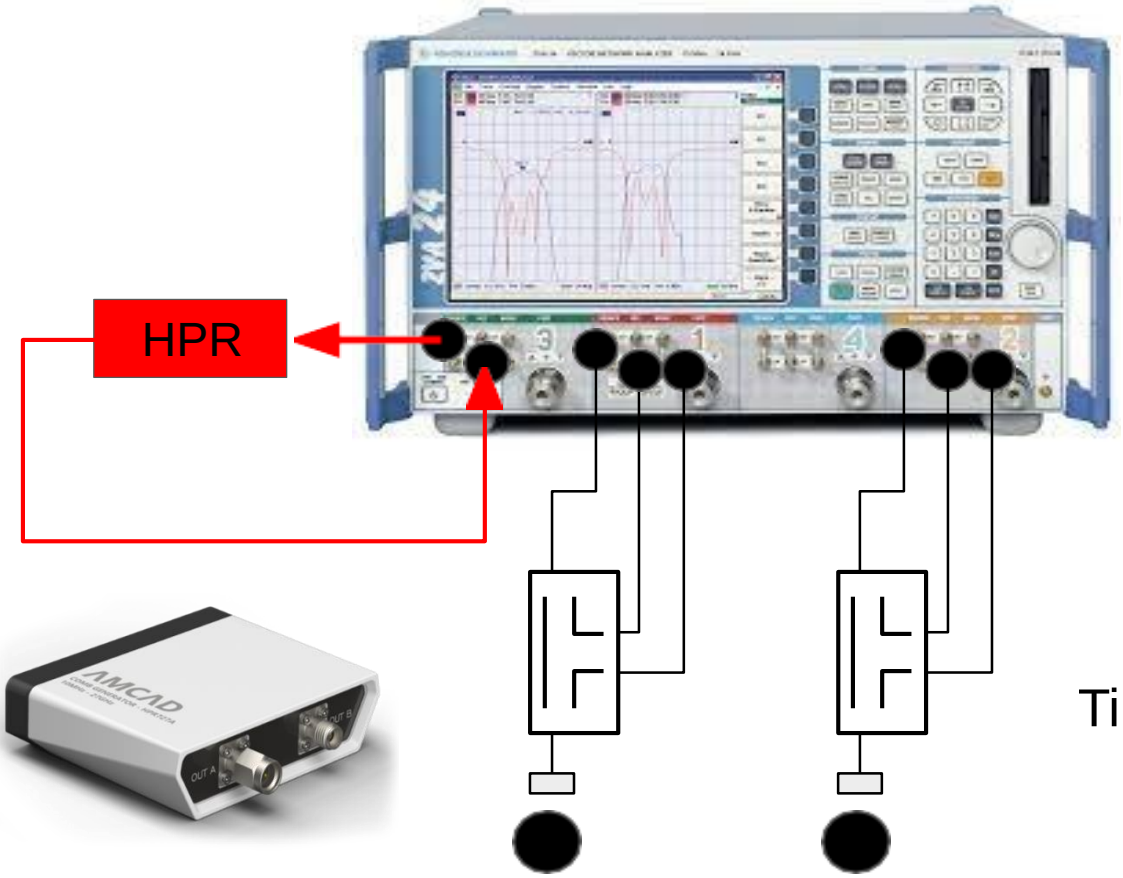


Outline of the presentation

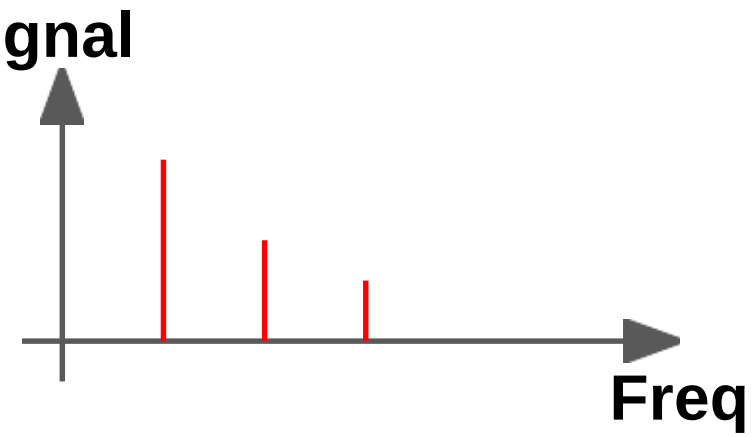
- Power-meter based measurements
  - Setup and calibration
  - Example on a Digital Doherty RF PA
  - Example on a Digital RF LMBA

- NVNA based measurements
  - Example on a Digital Outphasing RF PA
  - **Generalized NVNA Calibration**

Standard NVNA



AMCAD
HPR727A

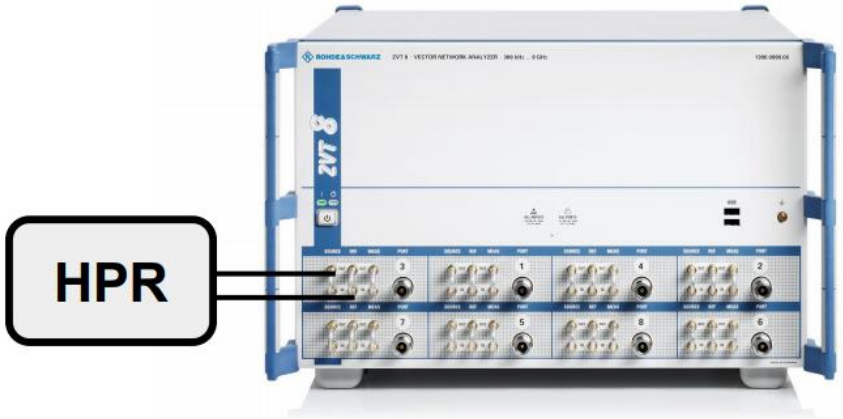


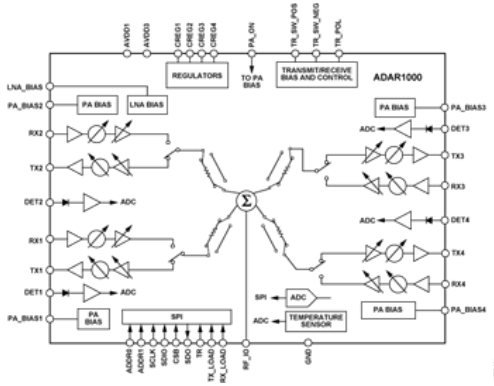
Time domain measurements:

- require a mandatory HPR ;
- require two independant RF sources ;
- require a 4-port VNA to make a 2-port NVNA ;

Multiport NVNA Setup

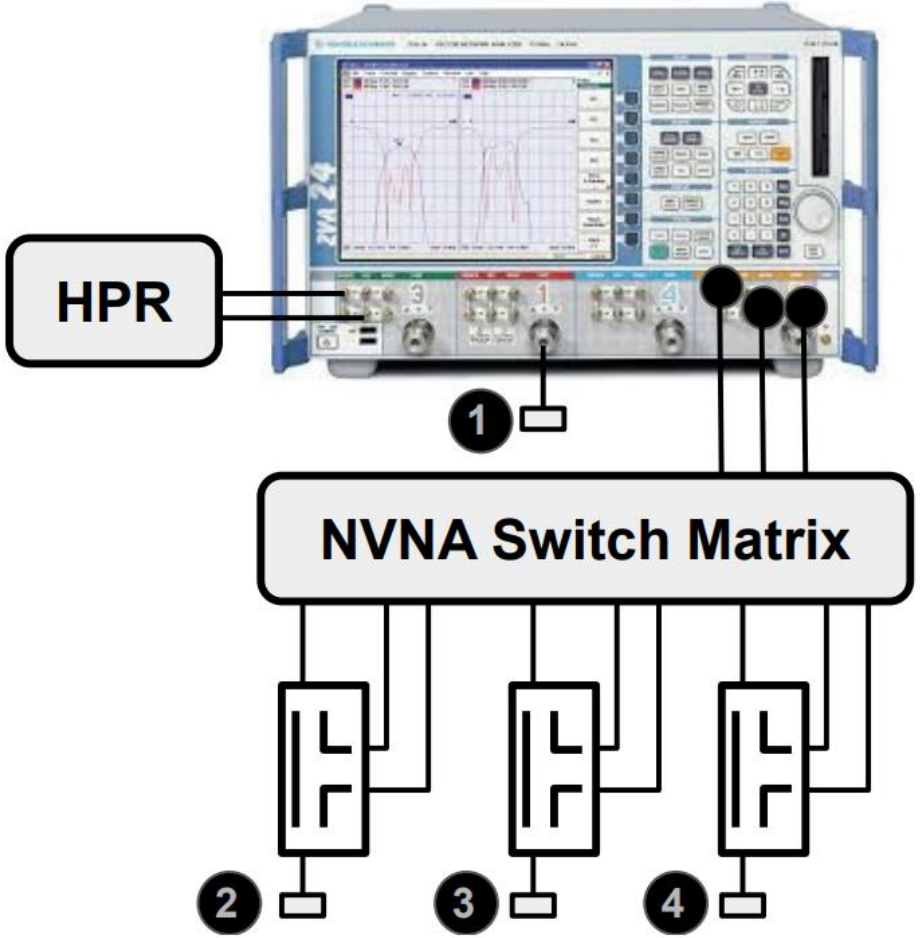
Direct receivers





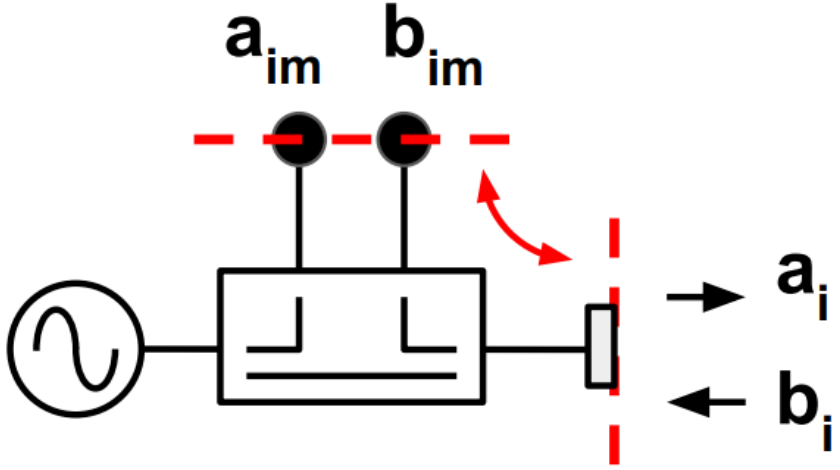
DUT Example: Beamformer by Analog Devices (ADAR 1000)

Switch Matrix



1-port SOL Calibration

$$\Gamma_{<std>} = \frac{b_i}{a_i} \quad \text{and} \quad \Gamma_{m<std>} = \frac{b_{im}}{a_{im}} \quad \text{with} \quad < std >= \text{Short ; Open ; Load}$$



$$\begin{pmatrix} a_i \\ b_i \end{pmatrix} = \alpha_i . \begin{bmatrix} 1 & \beta_i' \\ \gamma_i' & \delta_i' \end{bmatrix} . \begin{pmatrix} a_{im} \\ b_{im} \end{pmatrix}$$

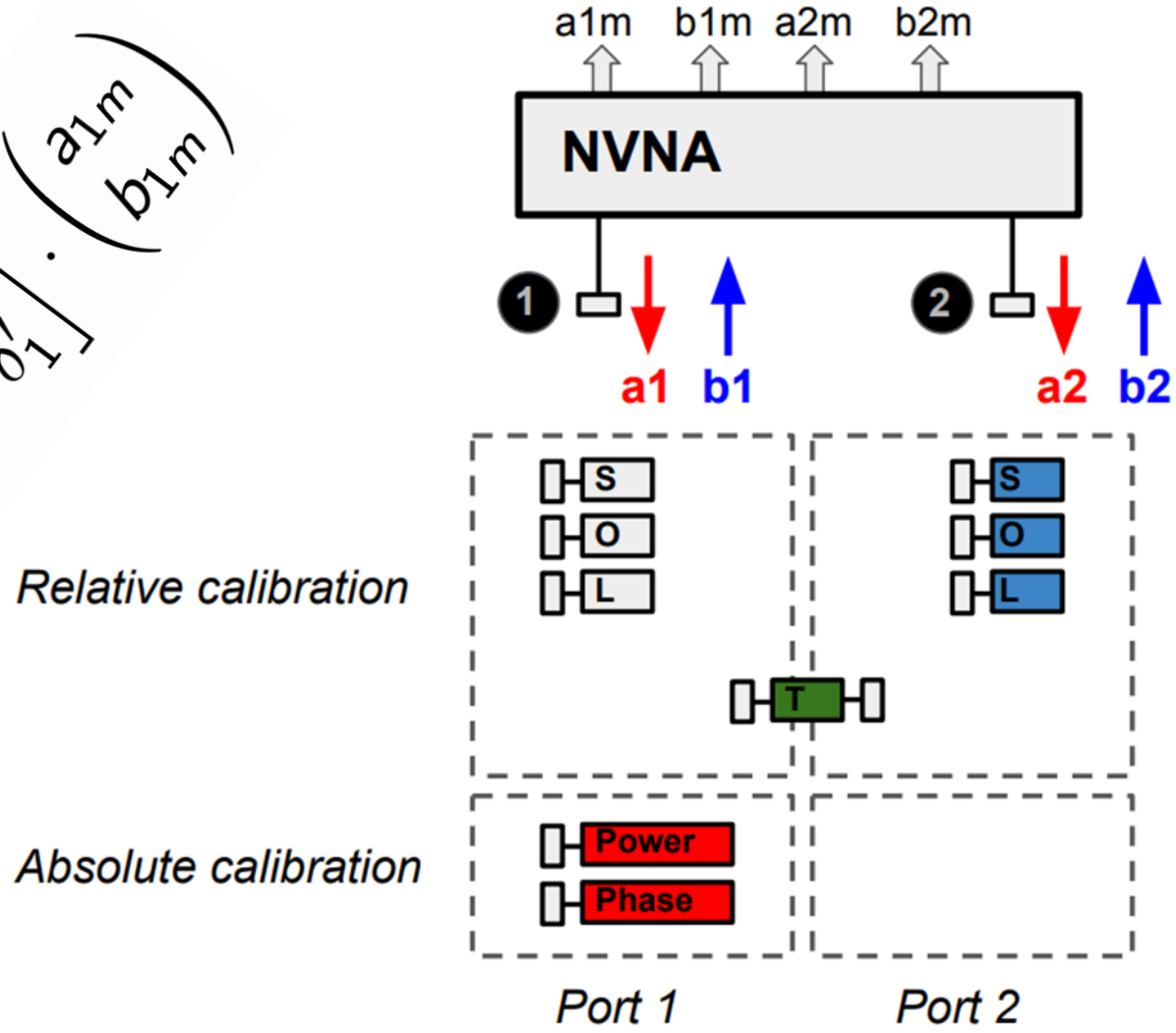
$$\Gamma_{<std>} = \beta_i' . \Gamma_{<std>} . \Gamma_{m<std>} + \gamma_i' + \delta_i' . \Gamma_{m<std>}$$

$$\begin{pmatrix} \Gamma_S \\ \Gamma_O \\ \Gamma_L \end{pmatrix} = \begin{pmatrix} \beta_i' \\ \gamma_i' \\ \delta_i' \end{pmatrix} . \begin{bmatrix} -\Gamma_{mS} . \Gamma_S & 1 & \Gamma_{mS} \\ -\Gamma_{mO} . \Gamma_O & 1 & \Gamma_{mO} \\ -\Gamma_{mL} . \Gamma_L & 1 & \Gamma_{mL} \end{bmatrix}$$

$$\begin{pmatrix} \beta_i' \\ \gamma_i' \\ \delta_i' \end{pmatrix} = \begin{bmatrix} -\Gamma_{mS} . \Gamma_S & 1 & \Gamma_{mS} \\ -\Gamma_{mO} . \Gamma_O & 1 & \Gamma_{mO} \\ -\Gamma_{mL} . \Gamma_L & 1 & \Gamma_{mL} \end{bmatrix}^{-1} . \begin{pmatrix} \Gamma_S \\ \Gamma_O \\ \Gamma_L \end{pmatrix}$$

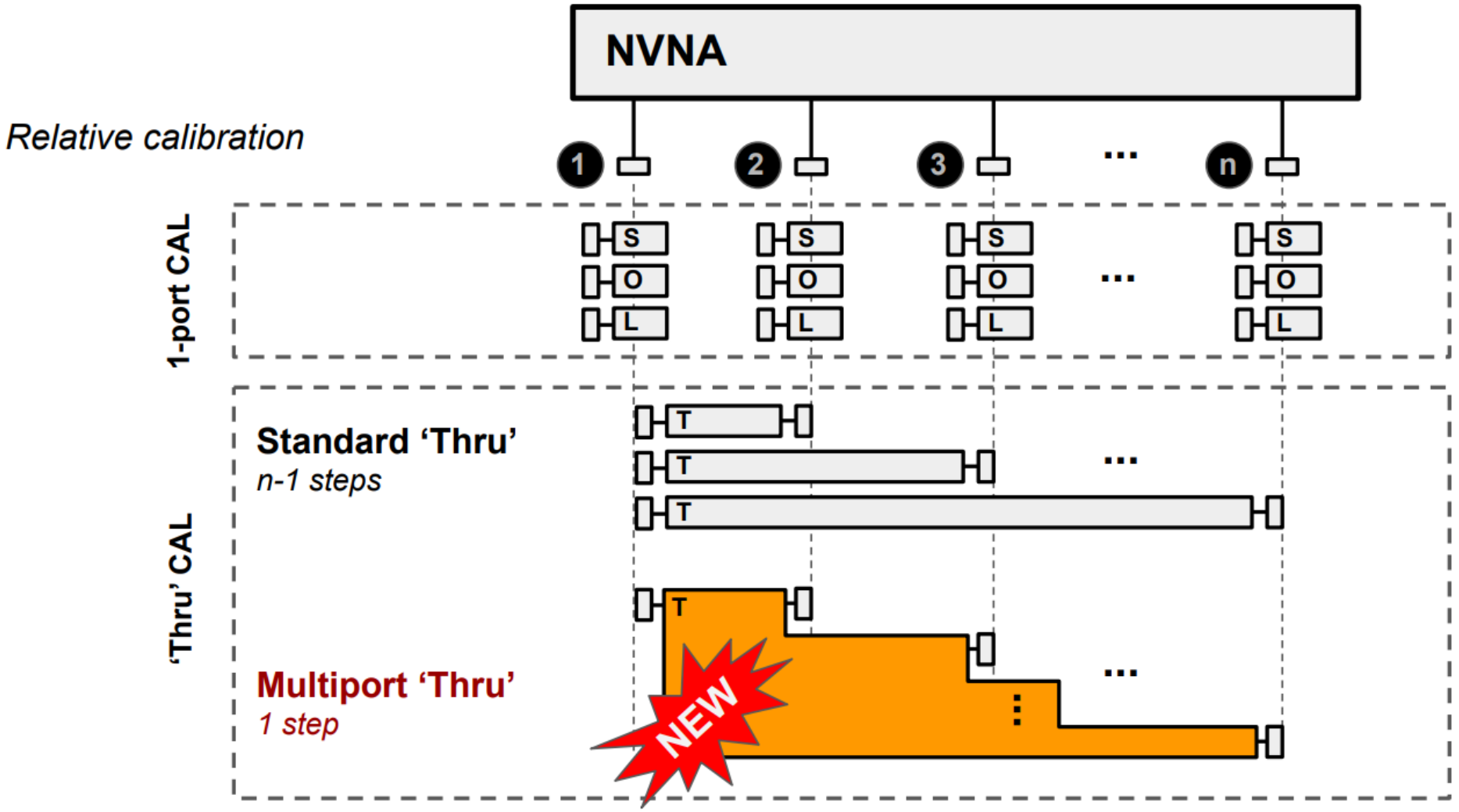
2-port NVNA Calibration

$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \alpha_1 \begin{bmatrix} 1 & \beta'_1 \\ \gamma'_1 & \delta'_1 \end{bmatrix} \cdot \begin{pmatrix} a_{1m} \\ b_{1m} \end{pmatrix}$$

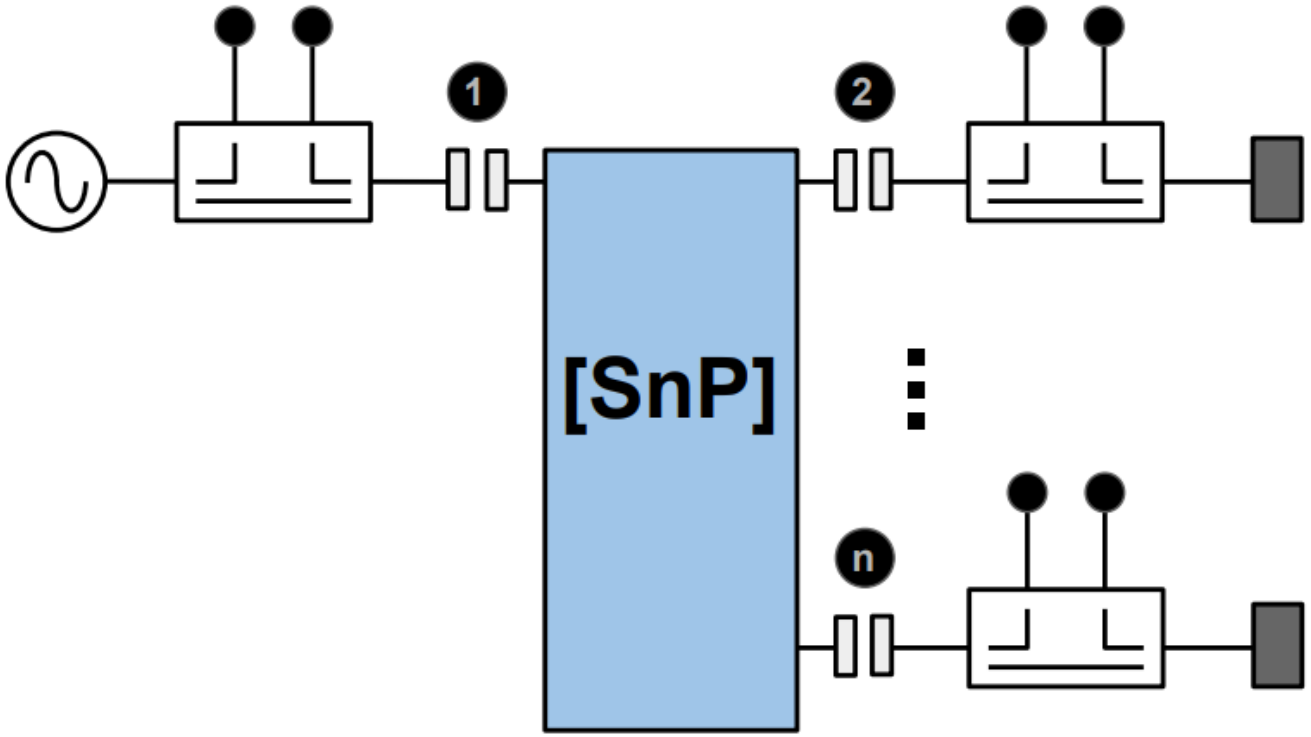


$$\begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = \alpha_2 \begin{bmatrix} 1 & \beta'_2 \\ \gamma'_2 & \delta'_2 \end{bmatrix} \cdot \begin{pmatrix} a_{2m} \\ b_{2m} \end{pmatrix}$$

N-port THRU Calibration



SOLT for multiport NVNA



$$\begin{pmatrix} \alpha_2 \\ \vdots \\ \alpha_n \end{pmatrix} = \left[\text{diag} \begin{pmatrix} \bar{b}_2 \\ \vdots \\ \bar{b}_n \end{pmatrix} - \begin{bmatrix} S_{22} & \dots & S_{2n} \\ \vdots & \ddots & \vdots \\ S_{n2} & \dots & S_{nn} \end{bmatrix} . \text{diag} \begin{pmatrix} \bar{a}_2 \\ \vdots \\ \bar{a}_n \end{pmatrix} \right]^{-1} . \bar{a}_1 . \begin{pmatrix} S_{21} \\ \vdots \\ S_{n1} \end{pmatrix}$$

2-port SOLR Method : Origins

A. Ferrero, U. Pisani, "Two-port network analyzer calibration using an unknown 'thru'" IEEE Microwave and Guided Wave Letters, Vol. 2, No. 12, 1992, pp. 505-507

Two-Port Network Analyzer Calibration Using an Unknown "*Thru*"

Andrea Ferrero, *Member, IEEE*, and Umberto Pisani

***Abstract*—A procedure performed by using a generic two port reciprocal network instead of a standard *thru* in a full two-port error correction of an automatic network analyzer is presented. Although it can be applied to any type of waveguide system the proposed technique is particularly useful with noninsertable coaxial or on-wafer devices. Experimental comparisons show that the suggested procedure provides a great degree of accuracy.**

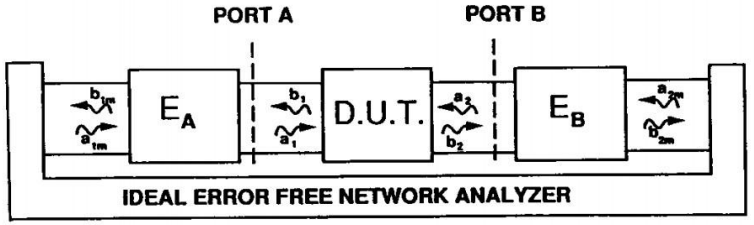
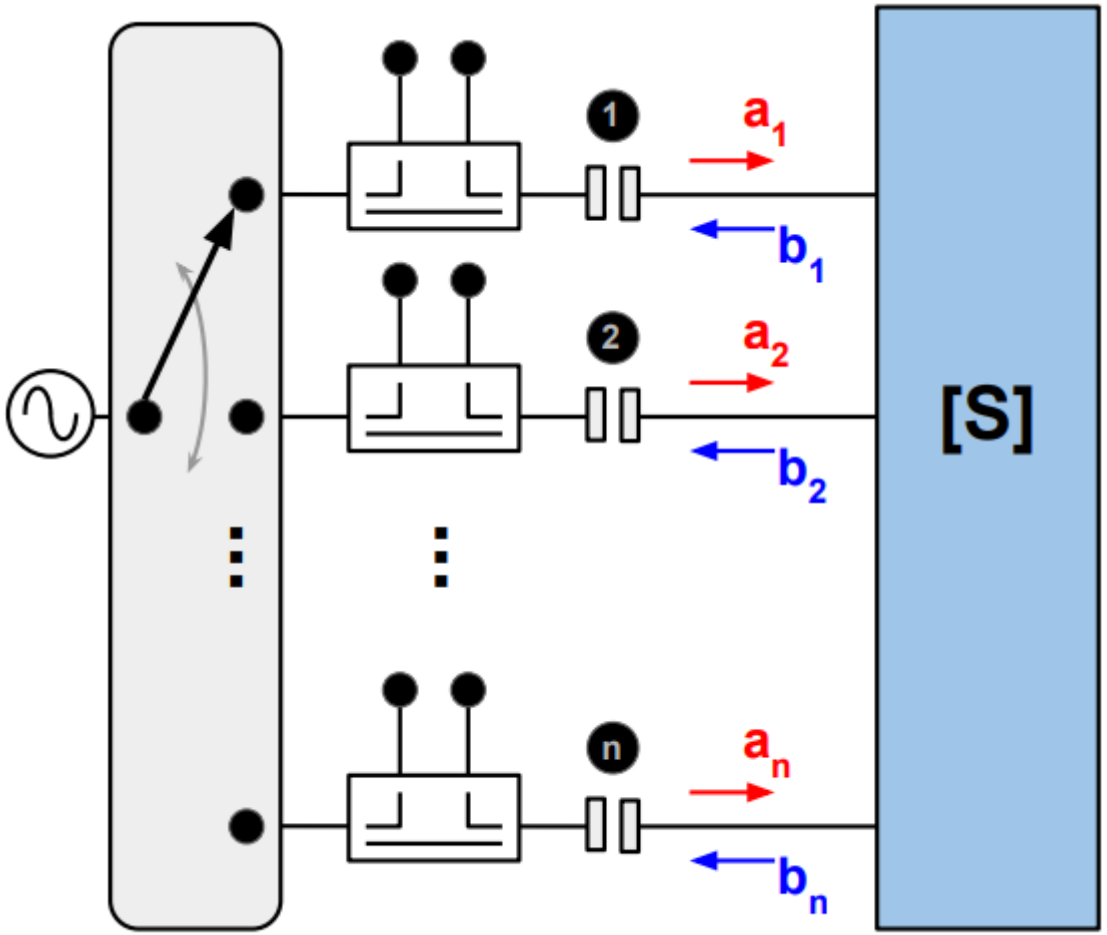


Fig. 1. Error box NWA model.

I. INTRODUCTION

SOLR for multiport NVNAs



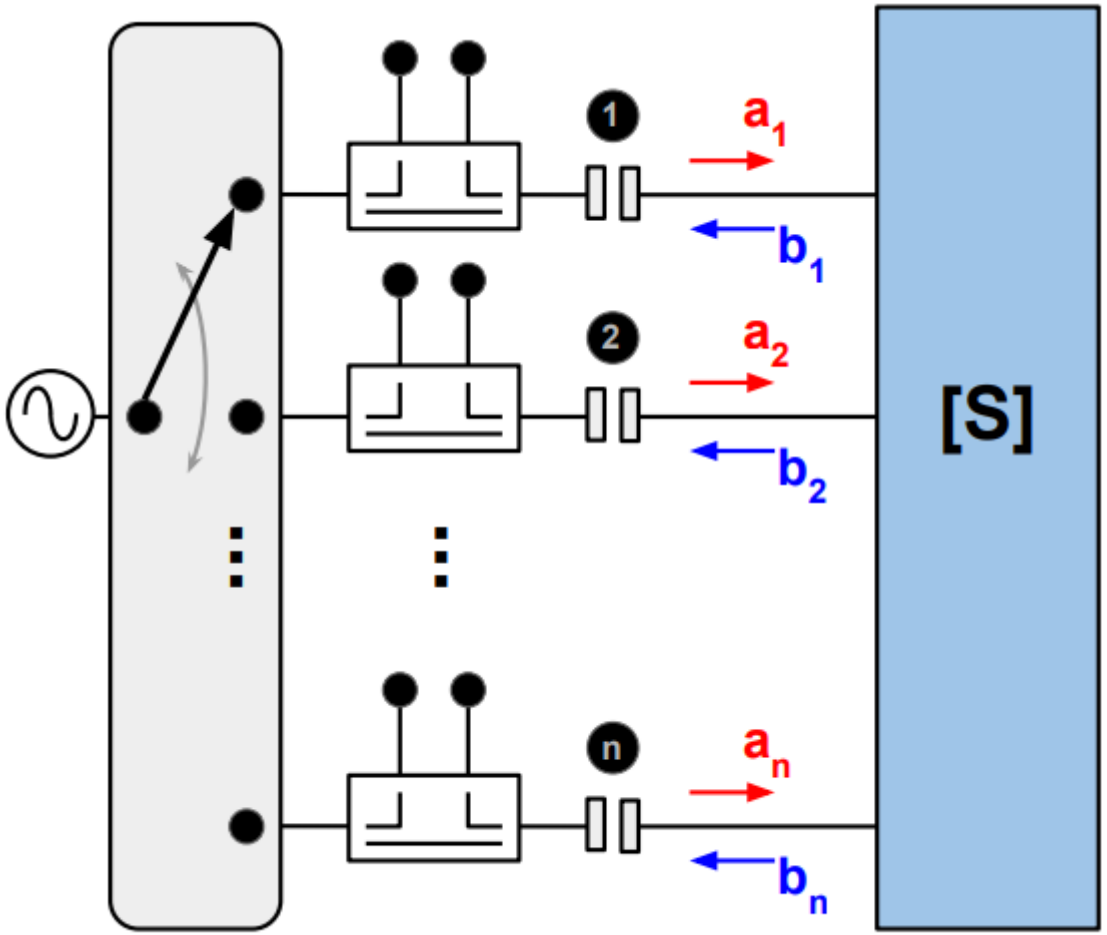
By definition :

$$[S] = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{bmatrix} \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}^{-1}$$

$\mathbf{a}_{ij}$ **:** wave **a** at port ***i*** when the RF source is active on port ***j***

SOLR: [S] is unknown but reciprocal ($S_{ij}=S_{ji}$)

SOLR for multiport NVNAs



Fully calibrated system: $[S] = [b_{ij}].[a_{ij}]^{-1}$

Partially calibrated system: $[\bar{S}] = [\bar{b}_{ij}].[\bar{a}_{ij}]^{-1}$

$$[S] = [\mathrm{diag}(\alpha_1, \ldots, \alpha_n)][\bar{S}][\mathrm{diag}(\alpha_1, \ldots, \alpha_n)]^{-1}$$

$$S_{ij} = \frac{\alpha_i}{\alpha_j}\bar{S}_{ij}$$

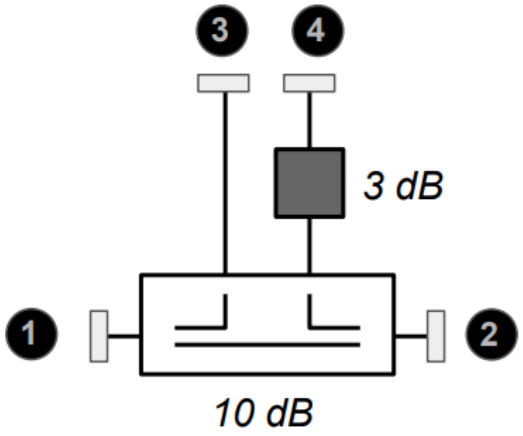
Reciprocity: $S_{ij} = S_{ji}$

$$\alpha_j = \pm\alpha_i . \sqrt{\frac{\bar{S}_{ij}}{\bar{S}_{ji}}}$$

The correct solution is selected according an estimation of $\mathrm{Arg}\{S_{ij}\}$

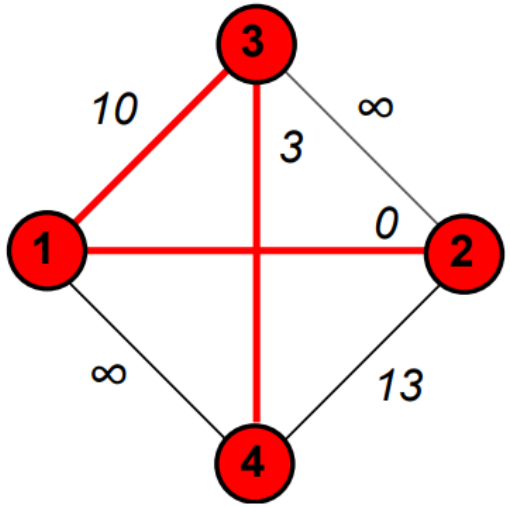
We start from $\alpha_1 = 1$ and then calculate α_i for $i = 2..n$

SOLR for multiport NVNAs



The Dijkstra Algorithm

Example on a non-ideal multiport “thru” standard



$$\alpha_1 = 1$$

$$\alpha_2 = \pm\alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$

$$\alpha_3 = \pm\alpha_1 \cdot \sqrt{\frac{\bar{S}_{13}}{\bar{S}_{31}}}$$

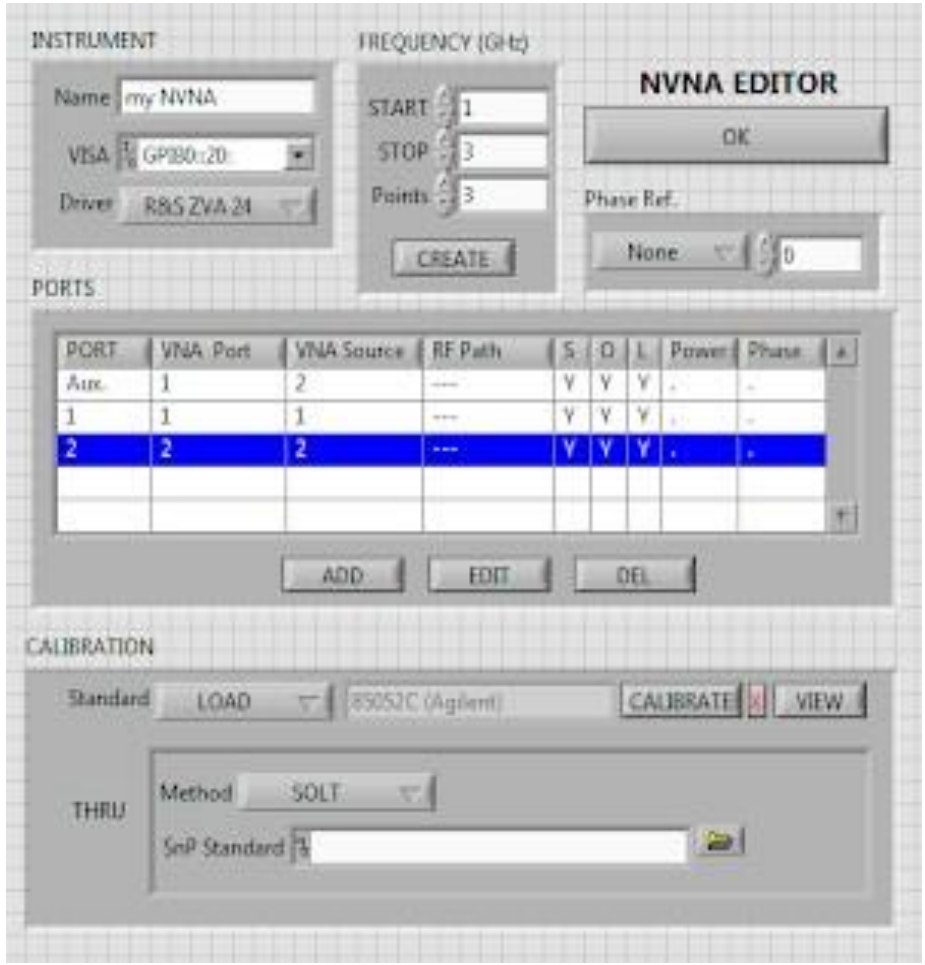
$$\alpha_4 = \pm\alpha_3 \cdot \sqrt{\frac{\bar{S}_{34}}{\bar{S}_{43}}}$$

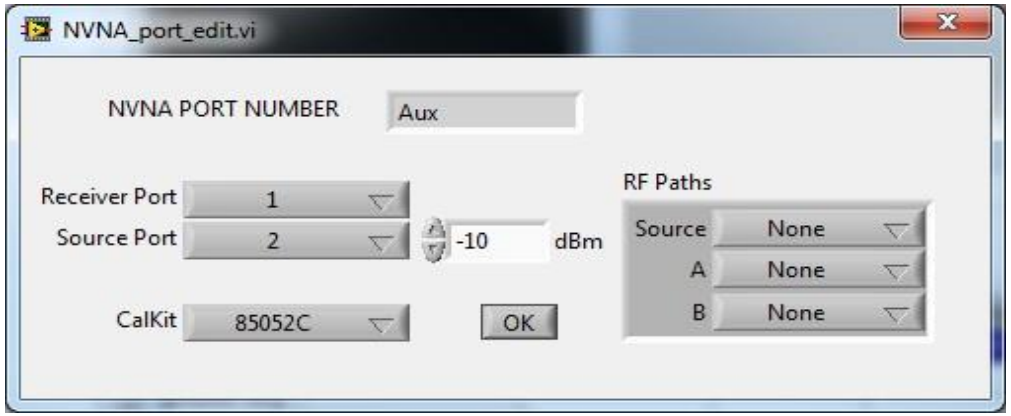
Calibration comparison on a 4-port system

[C] is highly isolated between ports 1 and 4

	Calibrated with [B]		Calibrated with [C]	
	SOLT	SOLR	SOLT	SOLR
Measured [B]				
Measured [C]				

Multiport NVNA object in LabVIEW





- Each port include its CalKit, RF power for calibration, Switch matrix configuration and physical source and receiver ports ;
- A NVNA is a unlimited array of predefined ports ;
- Once each port is SOL calibrated, “Thru” calibration require a SnP file for SOLT and SOLR.

Conclusion

Measurement setups and calibration methods

- Scalar measurements with power meters ;
- Vectorial measurements with a multiport NVNA.

Domain of Application

- Dual-input power amplifier analysis (Digital Doherty, Outphasing and LMBA)
- Beamformer behavioral modeling
- Nonlinear measurements for phased array antennas

IEEE references in this presentation

Doherty & LMBA (Power meters)

- **T. Reveyrand, A. Courty, M. Portelance, P. Medrel, P. Bouysse, J.-M. Nébus**
  «Automatic vector signal generator calibration method suitable for multiport large-signal measurements.»
  93rd ARFTG Symposium, IMS 2019, Boston, MA, June 2019.

Outphasing (LSNA)

- **M. Litchfield, T. Reveyrand, Z. Popović**
  «Load Modulation Measurements of X-Band Outphasing Power Amplifiers.»
  IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No 12, pp.4119-4129, December 2015.

Multiport SOLR (NVNA)

- **T. Reveyrand, S. Hernández, S. Mons, E. Ngoya**
  «SOLT and SOLR calibration methods using a single multiport "thru" standard connection.»
  95th ARFTG Symposium, IMS 2020, Los Angeles, CA, August 2020.